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Determining Geotechnical and Hydrogeological Parameters Using Downhole Geophysics in the Canadian Plains

Phase 2 Report

CORRELATIONS OF EXISTING DATA

May 1988

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TRANSALTA UTILITIES CORPORATION

on behalf of the

DOWNHOLE GEOPHYSICS
JOINT VENTURE RESEARCH GROUP

MICROMEDIA

246 pp

EXECUTIVE SUMMARY

The Downhole Geophysical Project resulted from the desire of several resource companies and geoscience consulting firms to improve the cost-to-data ratio of obtaining hydrogeological and geotechnical information for both coal and oil sands mining operations.

Proposals for joint industry and government research funding were prepared and submitted. The acceptance of these proposals for 50/50 industry/government funding by the Alberta and Canadian Governments resulted in the commencement of the project in November 1986. The project was divided into three phases, the results of the second phase being reported here.

The objective of the second phase is to evaluate through correlation whether various geotechnical and hydrogeological parameters could be obtained from downhole geophysics and to review which tools, not currently in use in Alberta, might have potential to provide the desired parameters.

This project used existing data that were collected with normal industry practices to develop site specific empirical correlations. The project has demonstrated that trends are present and correlations can be made but the variance of data scatter makes the direct use of the correlations questionable without further study.

Based on this program, one of the participants is investigating the use of the sonic log to determine the diggability of material in the selection of mining equipment.

At one coal mining operation, the geophysical logs that give the best correlations with geotechnical data are the Neutron, Density and Sonic Logs. The data also shows that good correlation was obtained between unconfined compressive strength and sonic transit time. For those relationships which exhibit correlation coefficients less than 0.8, the correlation may be improved by increasing the number of observations, by pairing combinations of parameters, by considering individual lithologic units or by more rigorous scrutiny of data to ensure consistency.

For one oil sands mining operation, the geophysical logs that provided trends were the Density and Gamma Logs when paired with different geotechnical parameters. All of the correlations have a wide scatter of data and could probably be improved by closer examination of the data.

Based on this study, it appears that the hydraulic conductivity cannot be estimated from geophysical parameters. Weak trends are indicated with the Density, Focussed Electric, and Neutron Logs. Additional analysis is required with existing data to further develop the data set used in the correlations.

A specifically designed program is recommended to obtain detailed geotechnical, geophysical, and hydrogeologic data from a series of carefully cored and logged holes. This should be done on a site specific basis in different types of coal or oil sands formations.

The programs should be run using the standard logging tools which include the gamma probe, the sonic tool, Neutron, and the gamma-gamma or density tool. If sufficient funds are available, a group of new tools such as the Radio Imaging Method and Thermal Logging Tools should be considered for future use.

Major problems were encountered in selecting and sorting of data. Existing data bases of geotechnical, geophysical and hydrogeologic data could not be easily related. These problems are discussed further in the text of the report.

Stricter recording of field data is required in field drilling and logging programs. This should include:

- tool calibration and field standardization
- borehole fluid conductivity and density
- exact location of geotechnical tests
- proper location of piezometer screens, sand pack in the aquifer zone

PREFACE

This report reviews the work done and results obtained in the use of existing downhole geophysical, geotechnical and hydrogeological data to determine the relationships between the borehole geophysics and the desired physical parameters. The results reported in the following chapters are based on the work completed as Phase 2 of the Downhole Geophysics Project undertaken as a joint industry/government research investigation. The project joint venture is funded by the following companies and organizations:

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Alberta Research Council (ARC)
CANMET: Energy, Mines and Resources, Canada through
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Fording Coal Ltd.
Klohn Leonoff Ltd.
Manalta Coal Ltd.
Monenco Consultants Inc.
Saskatchewan Power Corportaion
Suncor Inc., Oil Sands Division
Syncrude Canada Ltd.
Terracon Geotechnique Ltd.
TransAlta Utilities Corporation

The report has been written by several different authors and organizations and has been compiled by Klohn-Leonoff Ltd. and published by the Coal Mining Research Company.

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Lloyd Pitts	Monenco Consultants Ltd.
Neil Wade	Monenco Consultants Ltd.
Robert Wilson	Coal Mining Research Company (CMRC)

The Downhole Geophysics joint venture project is directed by a management committee chaired by Mr. Andrew Hickinbotham of TransAlta Utilities. TransAlta is acting on behalf of the industry joint venture participants for purposes of entering into Research Funding Contracts with Supply and Services, Canada and the Alberta Office of Coal Research and Technology.

The work plan organization, control and reporting was supervised by a Geotechnical Committee chaired by Mr. Geoff Jenkins of Manalta Coal and a Hydrogeological Committee chaired by Mr. Lloyd Pitts of Monenco Consultants Ltd.

In addition a panel of experts consisting of the following individuals reviewed the work in progress, commented on various drafts of this report and made many useful suggestions.

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S. Keys	U.S. Geological Survey (Retired)
P. Killeen	Geological Survey of Canada
N. Morgenstern	University of Alberta
J. Mwenifumbo	Geological Survey of Canada

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This report and its contents, the research project in respect of which it is submitted and the technology produced or demonstrated in the research project do not necessarily reflect the views of the Government of Alberta, its officers, employees or agents (or of the Alberta/Canada Energy Resources Research Fund Committee) or of the Members of the Office.

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DOWNHOLE GEOPHYSICS PROJECT

PHASE 2 - 1987/88

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1. INTRODUCTION

1.1 Project Formation

The Downhole Geophysics project was formed in the spring of 1986 by a group of resource and consulting companies which desired to find methods of reducing the cost of obtaining hydrogeological and geotechnical information for coal and oil sands mining operations.

Phase 2 of this project was conducted during the 1987/88 fiscal year under the direction of several working committees and a management committee chaired by Mr. Andrew Hickinbotham of TransAlta Utilities. The details of the management and technical committees are described in Appendix 1.

Funding for this phase of the project was provided by the industry participants on a 50/50 basis with the supporting government agencies. The coal portion was supported by the Alberta Office of Coal Research and Technology and the oil sands portion by Supply and Services Canada in cooperation with CANMET.

1.2 Background

The Phase 1 report (TransAlta Utilities Corp., 1987) described the potential for reducing costs to the western Canadian resource and consulting companies by the use of downhole geophysics to determine geotechnical and hydrogeological parameters. The initial review of the "state-of-the-art" reported in Phase 1 indicated that there were potential correlations between the downhole geophysics and some of the geotechnical and hydrogeological parameters of interest.

The recommendations to evaluate these suggested correlations on existing data formed the basis for Phase 2 of the project (reported here). As well, a more detailed review of geophysical tools which have not been tested in the western Canadian geological setting was recommended. This review was to determine which tools had the best chance of providing the desired parameters either directly or through simple correlations. Existing tools and those untested tools with the best chance of success will be field tested in Phase 3.

1.3 Objectives

1.3.1 Objectives of the Total Research Program

As outlined in the original proposals the objectives of the research program are to "... improve... and develop new techniques of using borehole geophysical data to determine geotechnical and hydrogeological characteristics of subsurface materials."

1.3.2 Objectives of Phase 2 (1987/1988)

The objective of Phase 2, conducted from April 1987 to March 1988, and reported here is "to evaluate the techniques identified in Phase 1 to obtain various geotechnical and hydrogeological parameters from downhole geophysics and to review which tools, not currently in use in Alberta, might have potential to provide the desired parameters."

The scope, objectives and methods of the subsequent phases will be modified to reflect the results and conclusions of the previous phases.

2. PROJECT APPROACH

2.1 Scope

The areas of interest for Phase 2 of this project were the correlations suggested in Phase 1 for which there were existing data which the project members could access. The availability of data, although known in general before Phase 2 started, was determined, in detail, as part of the work plan. The data collection and the correlations attempted are described in the technical chapters of this report.

2.2 Work Plan

The work plan generally follows the concept outlined in the original project proposals. The detailed work plan was generated at a project meeting held in conjunction with the expert panel to review the results of Phase 1 of the project. The revisions to the work plan were made to better reflect the results of Phase 1 and to recognize the limitations of data availability which were already apparent. This revised work plan is shown in Figure 1.

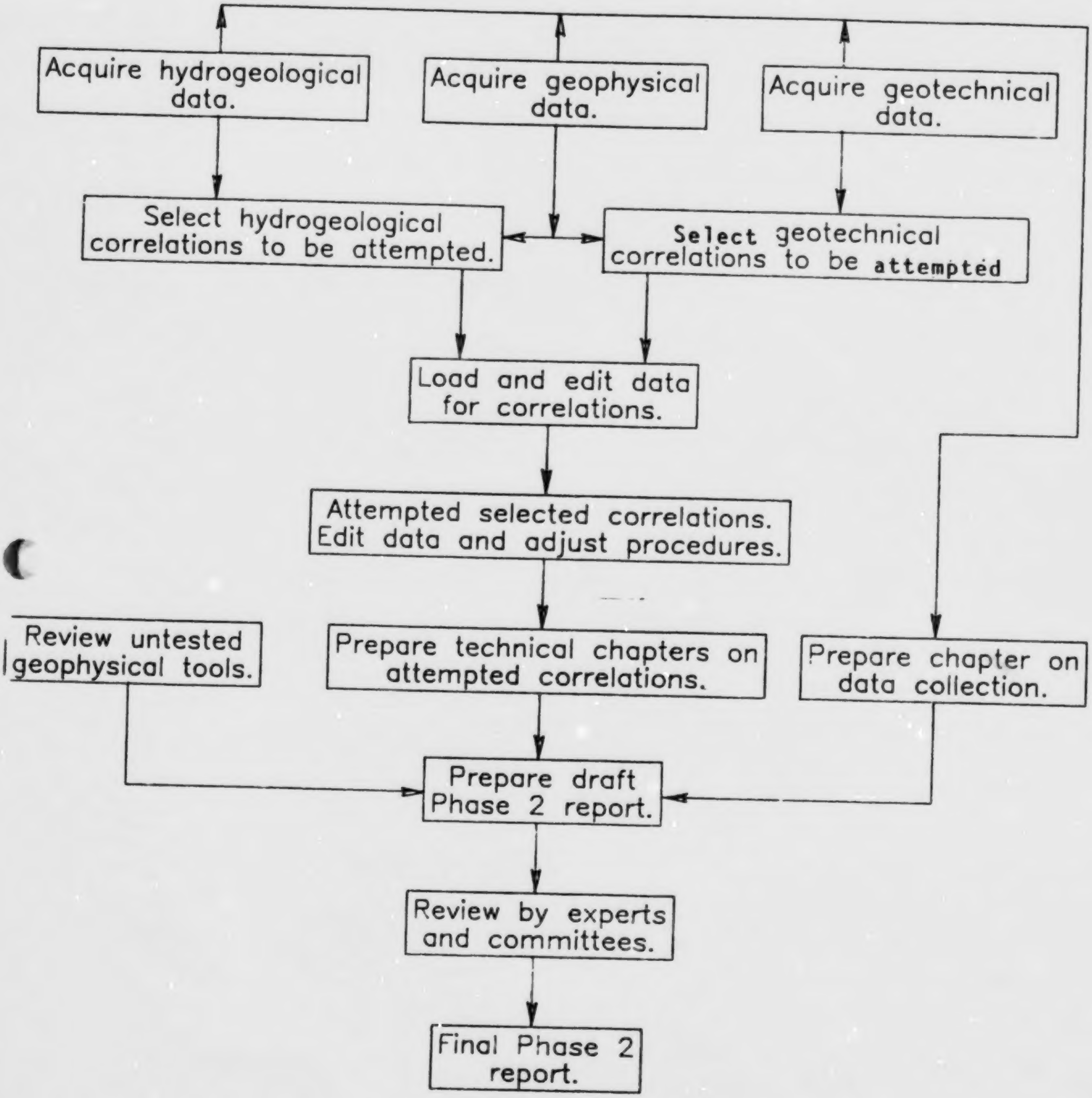
The data collection commenced by examining the participants' available data sets and selecting the matching geophysical and geotechnical or hydrogeological data for distribution to the groups working on the various correlations. The data was then loaded into a computer based manipulation system to allow the researchers to attempt the various suggested correlations. These correlations required, in some cases, editing and adjusting of the data to effect correct depth and composite relationships.

A review of the data collection procedures and the problems encountered is included in this report as well as a review of the correlations attempted and the procedures used.

As a preparation for the expected Phase 3 of the project, a detailed review of geophysical tools which have not been proven in the western Canadian plains environment was conducted. The objective of this review was to recommend which untested tools had the best chance of success in providing, either directly or by simple correlations, some of the geotechnical or hydrogeological parameters of interest. This review and associated recommendations are also included in this report.

The various reports, reviews and recommendations were collected and distributed as a rough draft report to the project members. The resulting revisions and comments were taken into account

DOWNHOLE GEOPHYSICS PROJECT
LOGIC DIAGRAM


Acquire hydrogeological data.
Acquire geophysical data.
Acquire geotechnical data.
Select hydrogeological correlations to be attempted.
Select geotechnical correlations to be attempted
Load and edit data for correlations.
Attempted selected correlations. Edit data and adjust procedures.
Review untested geophysical tools.
Prepare technical chapters on attempted correlations.
Prepare chapter on data collection.
Prepare draft Phase 2 report.
Review by experts and committees.
Final Phase 2 report.

Phase 2 Work—Plan

FIGURE 1

and resulted in this single report of Phase 2 of the Downhole Geophysics Project.

2.3 Data Sources

Early in the review of existing information, it was apparent that there was an extensive collection of geophysical data and test results available. These data were scattered between various coal and oil sands companies and several government organizations. The job of collecting, organizing, reviewing and distributing all this data in a consistent format was clearly beyond the scope of this project. It was agreed by the management committee to limit the data search to those organizations participating in the project and to chose at least one data set for coal formations and one for the oil sands formations.

The data search took several stages. First the participants were asked to provide a rough estimate of the number of boreholes which had been geophysically logged and had at least some geotechnical or hydrogeological tests. The participants responded either formally or informally. From this survey, those companies or data sources with the widest variety of geophysical tools and geotechnical testing were chosen to provide the data to the Project.

TransAlta was chosen as one of the geotechnical data sources in part because of its large computer data base and because of its coal mining experience in the Western Plains geologic conditions. Highvale Mine was chosen to provide geophysical and geotechnical data as a representative of the coal industry. The Alberta Research Council (ARC) was chosen as a source of hydrogeologic data because of its expertise and varied work experience in the province. Syncrude was chosen as representative of oil sands mining operations that could provide good quality data from a select drilling program. The locations of the three chosen data sources are shown on the following map as Figure 2. A concerted but unsuccessful attempt was made to obtain data from the Alberta Oil Sands Technology and Research Authority (AOSTRA) underground test facility project in time for inclusion into the Project.

Subsequently, the selected data contributors needed to identify the number and type of tests available with what specific geophysical logs. Furthermore, it was useful to segregate this data into groups according to rock types where possible to determine whether correlations could be made for all rock types. For example, would there be sufficient number of compressive strength tests to allow development of a correlation curve covering a wide assortment of rock types?

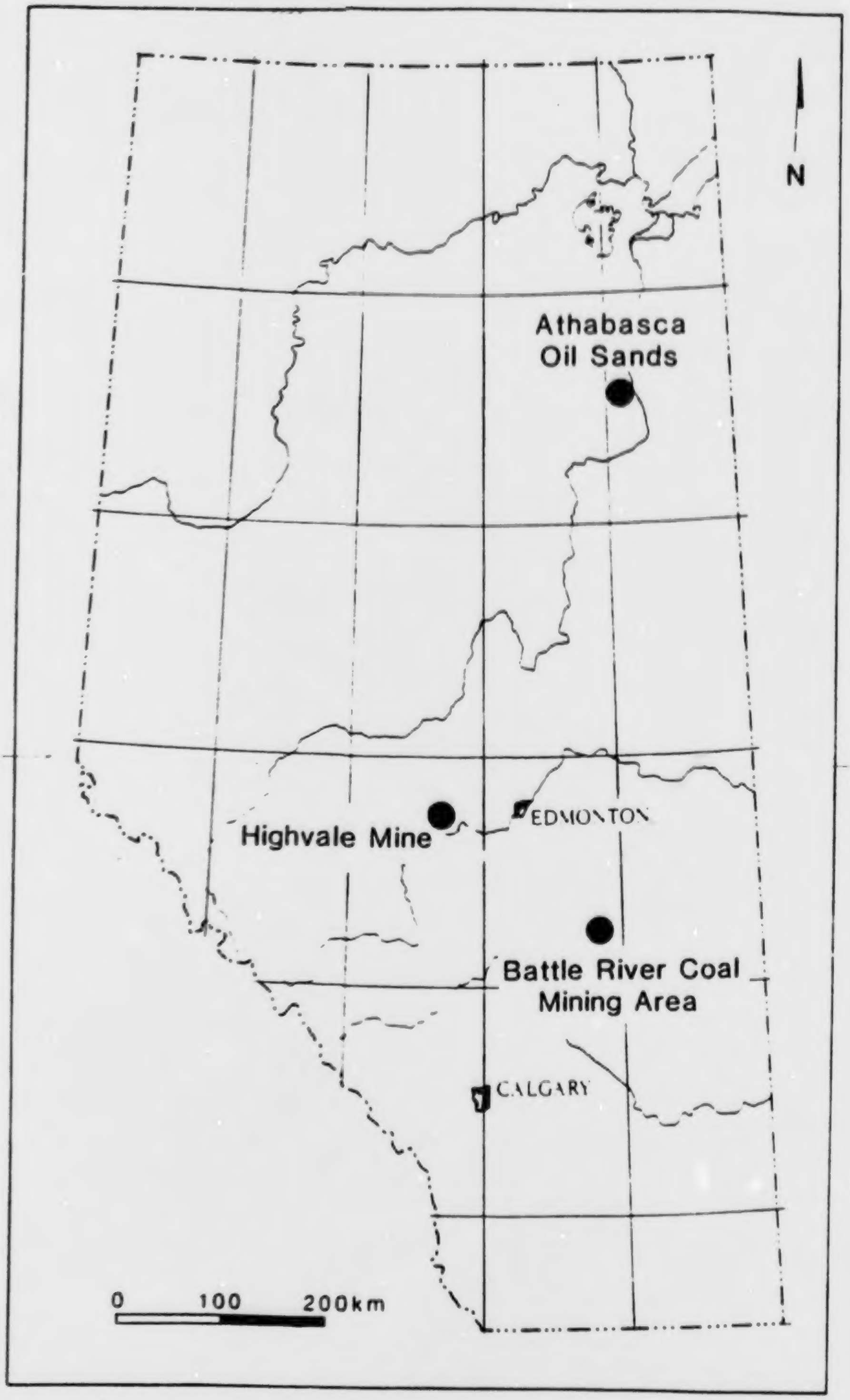

N
Athabasca Oil Sands
Highvale Mine
EDMONTON
Battle River Coal Mining Area
CALGARY
0
100
200km

Figure 2 Location of data sources, Highvale Coal Mine, Battle River Coal Mining area and Athabasca Oil Sands area.

As originally envisioned, data were to be collated under one data base so that the data could be independently assessed by several investigators. However, overcoming the problems in electronically transferring data from varying computer system types, makes and formatting would require considerable effort. Further, not all the data was in electronic form. It was decided that it would be more efficient to evaluate each data set separately. This method also had the added benefit of ensuring the confidentiality of data.

A detailed description of the data sets for the two geotechnical and one hydrogeological evaluation are included with the relevant sections of this report.

2.4 Geological Settings

The Alberta coal and oil sands deposits lie within poorly lithified clastic sediments that were deposited in deltaic, fluvial and estuarine environments during Jura-Cretaceous and younger times. The sediments are characterized by variations in lithology, both horizontally and vertically, over very short distances, so that it is often difficult to correlate rock types, geotechnical characteristics, hydrogeological parameters, etc. without closely spaced drilling.

In addition to their stratigraphic complexity, the deposits have received varying degrees of tectonic deformation. The deposits of the Foothills and Mountain regions are strongly deformed, and are characterized by folds, a variety of types of faults, sheared zones, and joints. The Plains deposits (including oil sands) exhibit less faulting and little folding, but are jointed and in some areas have suffered glaciotectonic deformations, thereby contributing to their inherent weakness.

The TransAlta coal data is taken from the Highvale Mine area which is part of the Ardley coal zone. The hydrogeological data used by the Alberta Research Council were collected from coal exploration drilling in the Battle River area east of Red Deer. To better illustrate the general statigraphy in the areas of selected data, typical stratigraphic columns are presented for the Athabasca Oil Sands and the Highvale and Battle River areas on Figures 3 and 4.

All of the information for the oil sands geotechnical work was provided by Syncrude from drilling and testing on their current leases in the McMurray Formation near Ft. McMurray. The data are from the Lower Cretaceous Clearwater Formation, a marine deposit that has been heavily over-consolidated. The Clearwater Formation consists of clays, silts and some sands which were deposited in a shallow epicontinental sea approximately ninety million years ago. The Clearwater Formation comprises the bulk of the overburden deposits on the two leases with the exception of a thin veneer of glacial sediments which average five to seven metres in thickness. A schematic cross section of the Syncrude Lease is shown on Figure 5.

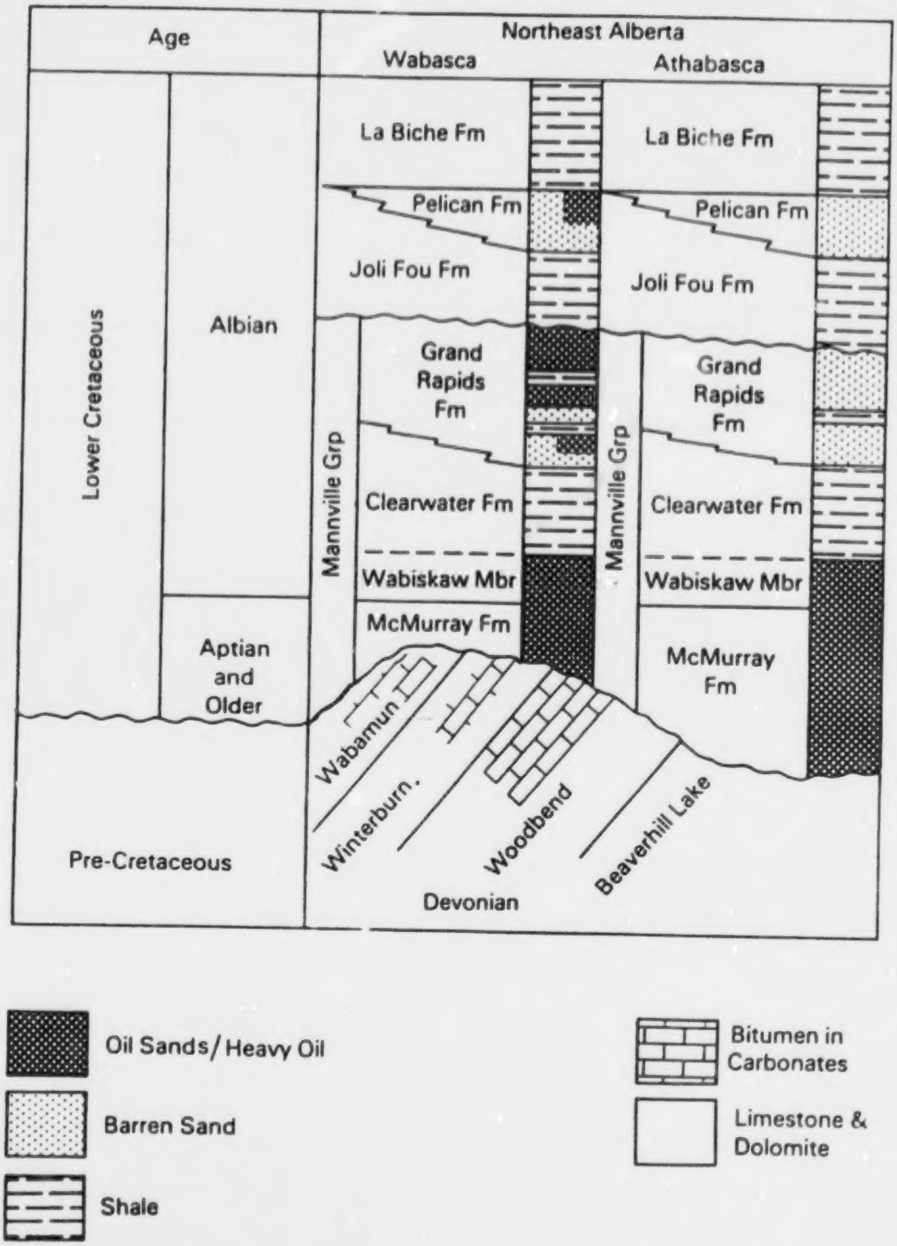

Age
Northeast Alberta
Wabasca
Athabasca
Lower Cretaceous
Albian
Aptian and Older
Pre-Cretaceous
La Biche Fm
Pelican Fm
Joli Fou Fm
Grand Rapids Fm
Clearwater Fm
Wabiskaw Mbr
McMurray Fm
Mannville Grp
La Biche Fm
Pelican Fm
Joli Fou Fm
Grand Rapids Fm
Clearwater Fm
Wabiskaw Mbr
McMurray Fm
Mannville Grp
Wabamun
Winterburn
Woodbend
Beaverhill Lake
Devonian
Oil Sands/Heavy Oil
Barren Sand
Shale
Bitumen in Carbonates
Limestone & Dolomite

Figure 3 Stratigraphy of Athabasca Oil Sands area (modified from Kramers and Mossop, 1987).

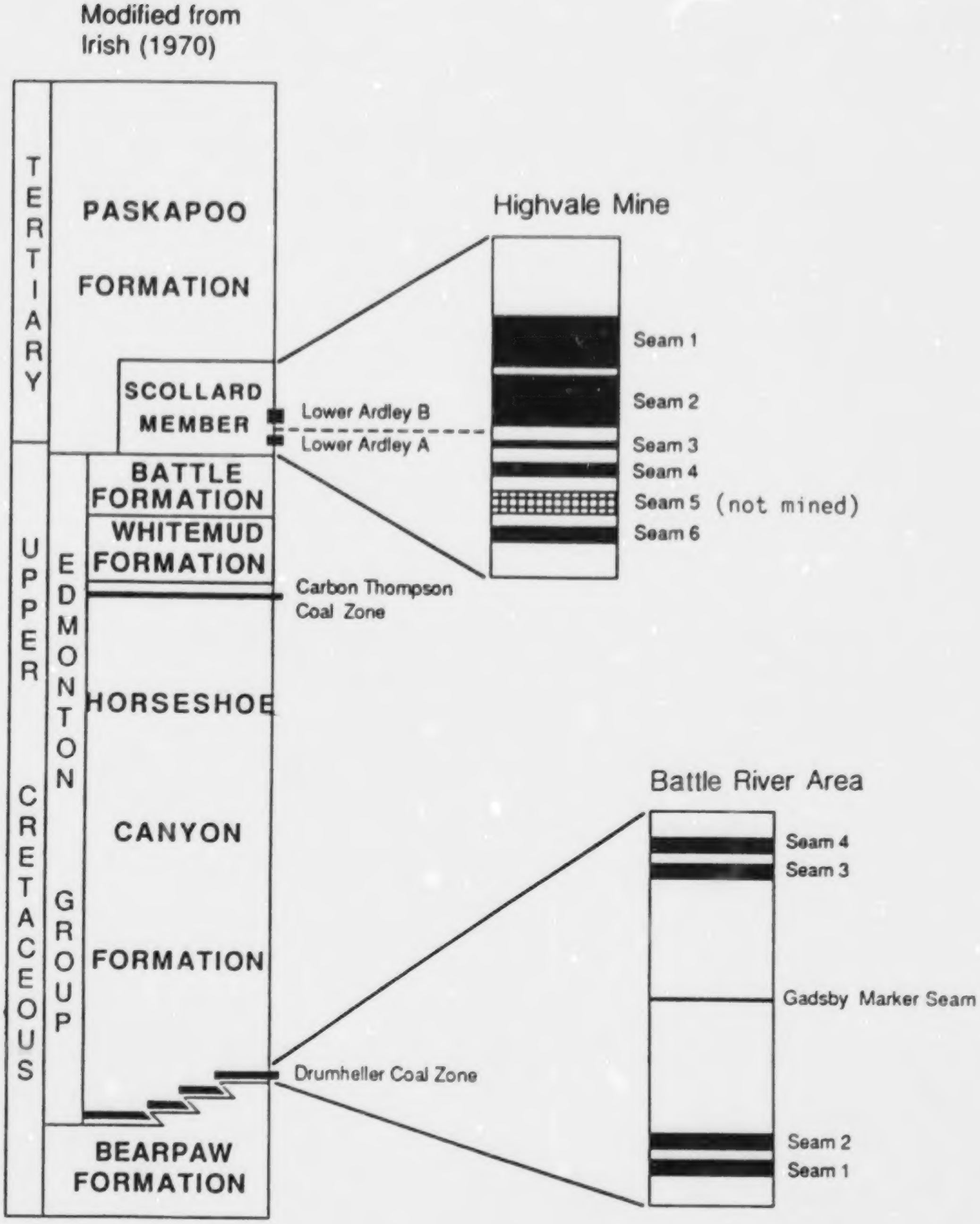
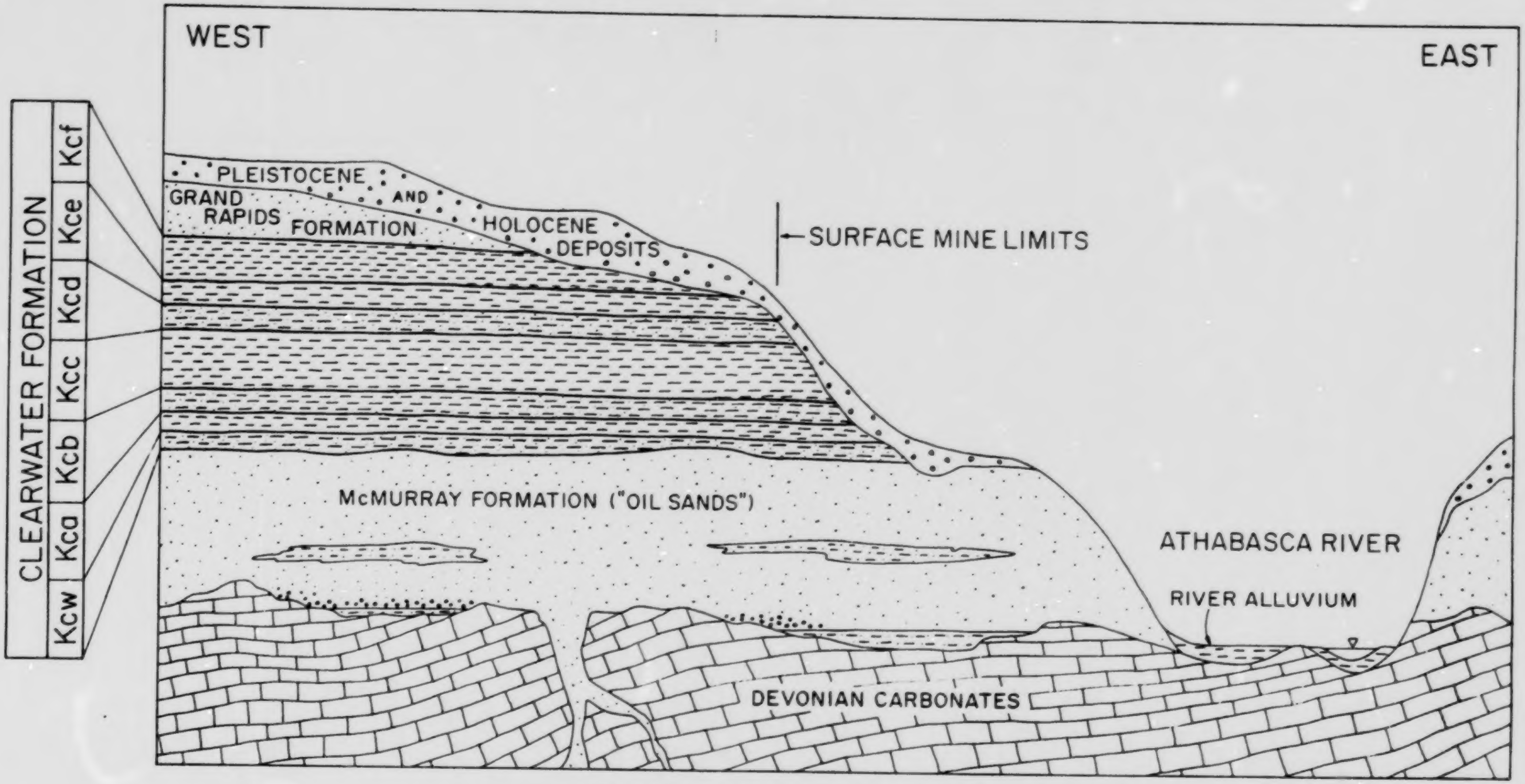

Modified from
Irish (1970)
TERTIARY
PASKAPOO
FORMATION
SCOLLARD
MEMBER
Lower Ardley B
Lower Ardley A
UPPER CRETACEOUS
EDMONTON GROUP
BATTLE
FORMATION
WHITEMUD
FORMATION
Carbon Thompson
Coal Zone
HORSESHOE
CANYON
FORMATION
Drumheller Coal Zone
BEARPAW
FORMATION
Highvale Mine
Seam 1
Seam 2
Seam 3
Seam 4
Seam 5 (not mined)
Seam 6
Battle River Area
Seam 4
Seam 3
Gadsby Marker Seam
Seam 2
Seam 1

Figure. 4. Stratigraphy of Highvale and Battle River areas.


WEST
EAST
CLEARWATER FORMATION
Kcf
Kce
Kcd
Kcc
Kcb
Kca
Kcw
PLEISTOCENE AND HOLOCENE DEPOSITS
GRAND RAPIDS FORMATION
SURFACE MINE LIMITS
McMURRAY FORMATION ("OIL SANDS")
ATHABASCA RIVER
RIVER ALLUVIUM
DEVONIAN CARBONATES

SCHEMATIC CROSS-SECTION
SYNCRUDE CANADA LTD. LEASES

≈50X VERTICAL EXAGGERATION

FIGURE 5

3. GEOTECHNICAL - COAL FORMATIONS

3.1 Data Search

In TransAlta's experience, electronic data base manipulation was more cumbersome than expected. The time expended in learning to retrieve data was a result of having more experience in storing data than retrieving it. This is a common problem since data entry is a repetitive, labour intensive effort where as data requests can be quite varied and often unique.

An example of the kind of problems encountered was the difficulty in retrieving geotechnical data by lithology type. This was because searching by lithology is done through the geologic log rather than through the description of the sample taken for geotechnical testing. Because the geotechnical sample interval is usually much smaller than the geological interval, often the geologic description differs from the geotechnical description. This problem was resolved but entailed manual sorting of data.

These and other problems arose mainly from the structure of the data base. This is not surprising since it would have been difficult at the time the data base was set up to envision the connection between geotechnical, geophysical and geological data.

Retrieval of geophysical logs alone was efficiently done through a log analysis program called Terralog. Despite little experience with this program, data were easily retrieved through a menu-driven program and transferred to a PC computer for data analysis.

Unfortunately, older geophysical data were not in good order and many tapes could not be read due to procedure and equipment changes over the years. For example, the older tapes needed to be reformatted from the older 800 bits per inch (bpi) format to the newer 1,600 bpi. As well, 10 cm reading spacing were changed to 1 cm spacing for greater detail. While these problems were easily resolved, it did cause delays and subsequently some data were not available at the time of data analysis. Geophysical data collected in recent years are in good shape probably because of the increased use of geophysics in identifying lithology.

Initial data base queries revealed that there were some 877 boreholes. These boreholes which were located in the Highvale Mine, the Whitewood Mine and the Low Water Lake area; containing varying degrees of geotechnical and geophysical data. Due to time constraints and formatting problems with early geophysical data, only 1982 and subsequent data from Highvale Mine was used in this study.

Geotechnical data were retrieved from the TransAlta geotechnical data set and the suite of geophysical logs, corresponding to the same lithology and stratum depth interval as the geotechnical test specimens, obtained from the Terralog tapes at TransAlta.

3.2 Methodology

The geotechnical and geophysical data were supplied by TransAlta on floppy discs in the Lotus 1-2-3 format and on hard copy. Monenco rearranged these data to create a series of files containing drillhole number, depth interval, material type, selected geotechnical parameters and corresponding geophysical log values. Statistical regression analyses were utilized to characterize the relationships between individual geotechnical parameters and the geophysical log values corresponding to the same stratum depth interval. Geotechnical parameters selected were:

- uniaxial compressive strength
- natural moisture content (based on oven-dry weight)
- liquid and plastic limits
- bulk density

Geophysical log data were supplied in digitized format at 1 cm depth intervals and included the following logs:

- Gamma
- Density
- Resistivity
- Neutron
- Sonic
- Caliper

The Lotus 1-2-3 statistical, and XY graphics packages were used in the data pairing procedures. In addition, the statistical method of regression analysis for obtaining the best-fit polynomial equation was conducted manually for correlating the uniaxial compressive strength with sonic transit time to obtain a higher correlation coefficient than was possible with the Lotus package. The correlations obtained by these procedures are primarily empirical since no attempt was made to establish a theoretical basis for the relationships.

In carrying out the correlations, it was found that the scatter of plotted data was significantly reduced when the procedures outlined in the following were adopted.

3.2.1 Qu vs Sonic Transit Time

To avoid excessive data scatter and obtain the best correlations between the uniaxial compressive strength, Qu, and sonic transit time, the following procedure was established:

- Adjust the depth interval location, where necessary, of the uniaxial compression test results to agree with the lithology depth interval determined from geophysical logs.

- Use the average value of the sonic log spacing signature (Channel 3 on the BPB probe) over the stratum thickness being considered. Minimum acceptable stratum thickness = 1.5 times Channel 3 receiver spacing.

- Use digitized sonic transit time readings at 1 cm intervals of borehole depth.

- Do not use sonic data if the borehole diameter varies as denoted by the caliper log by more than 0.1 inch over the depth interval considered.

- Do not use sonic data if any of the three sonic log (short, medium and long) values remain constant over the depth interval.

3.2.2 All Other Correlations

Once each spreadsheet file containing the geotechnical parameter(s) being considered and the corresponding geophysical log(s) was set up from the base data, the file was condensed to eliminate rows containing missing data. Thus only those geotechnical data values which corresponded to a complete suite of geophysical logs were used for establishing the correlations.

3.3 Tools and Tests

The type of geotechnical tests commonly conducted range from triaxial compression tests to Atterberg Limits as indicated in Table 1. All testing conformed to ASTM standards except when laboratories were instructed to deviate from the prescribed ASTM procedures, as for example, when the samples are blenderized in preparation for the Atterberg Limits test.

Table 1

LIST OF GEOTECHNICAL TESTS

Geotechnical Test	Properties
Moisture Content	moisture, degree of saturation
Atterberg Limits	plasticity
Consolidated Undrained Triaxial	shear strength
Unconsolidated Undrained Triaxial	compressive strength
Direct Shear	shear strength
Bulk Density	weight
Grain Size	particle size variation
Pocket Penetrometer	strength, density, consistency
Vane	strength, density, consistency
Cone Penetrometer	strength, density, consistency
Standard Penetration Test	strength, density, consistency

Both Century Geophysical Corporation and BPB Instruments Ltd. have been used in the past to log the boreholes. The data used in this report, with few exceptions, has been provided by BPB tools which are listed in Appendix II.

Typical log response ranges for each tool and rock type found at the Highvale Mine are presented in Figure 6.

3.4 Correlations

A summary of the correlations established between geotechnical and geophysical parameters is given in Table 2 and a list of the geophysical log cross-plots obtained is shown in Table 3. Also included in each table are the respective correlation coefficients and number of observations for each relationship. Graphs depicting the more promising correlations are included in Appendix III.

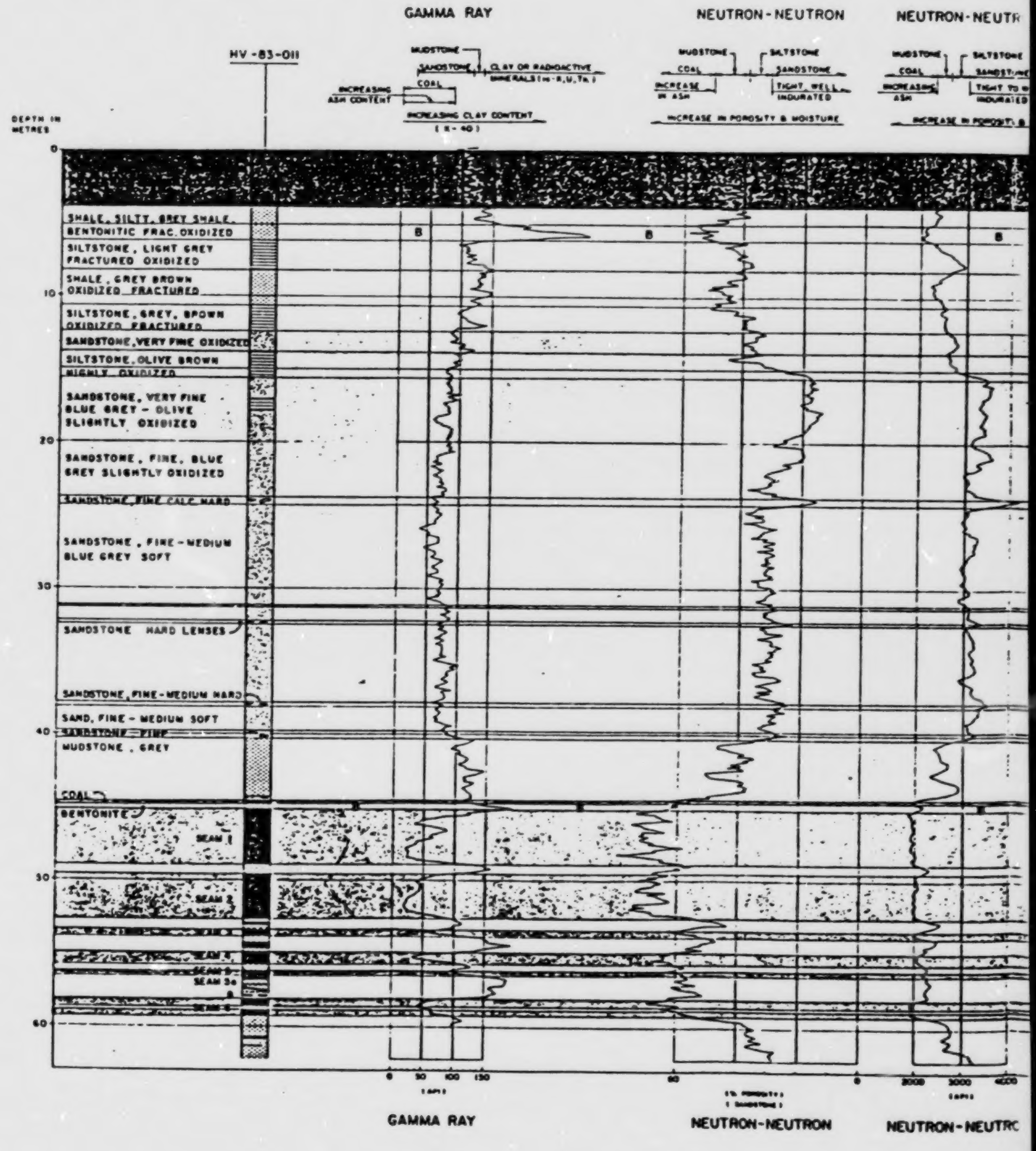
Each of the correlations and cross-plots included symbols for the main overburden lithological units which are comprised of sandstone, siltstone, mudstone and bentonite. Due to time constraints, however, no attempt was made to develop correlations for individual lithologies.

In addition, parameters for glacial till, which mantles the Highvale area to an average depth of about 5 m, were not correlated.

3.5 Discussion

Apart from the procedures outlined in Section 3.2, no attempt was made to evaluate and cull the data to generate optimal correlations. Most of the correlations were developed using linear regression analyses but, as indicated for the Qu vs Long Sonic relationship in Table 2, it may also be possible to upgrade correlations for some data pairs by fitting polynomial curves rather than straight lines to the plotted data. This is illustrated in Figure 7 which shows plots of Sonic Travel Time against uniaxial compressive strength.

It is probable, however, that the equations shown in Tables 2 and 3 would change if the number of observations were substantially increased. Furthermore, it is not known to what extent the relations obtained are site specific since comparison of the Highvale data with data from other sites was not done.



A SUITE OF LOGS RUN TO SHOW TYPICAL RESPONSE C

REVISIONS

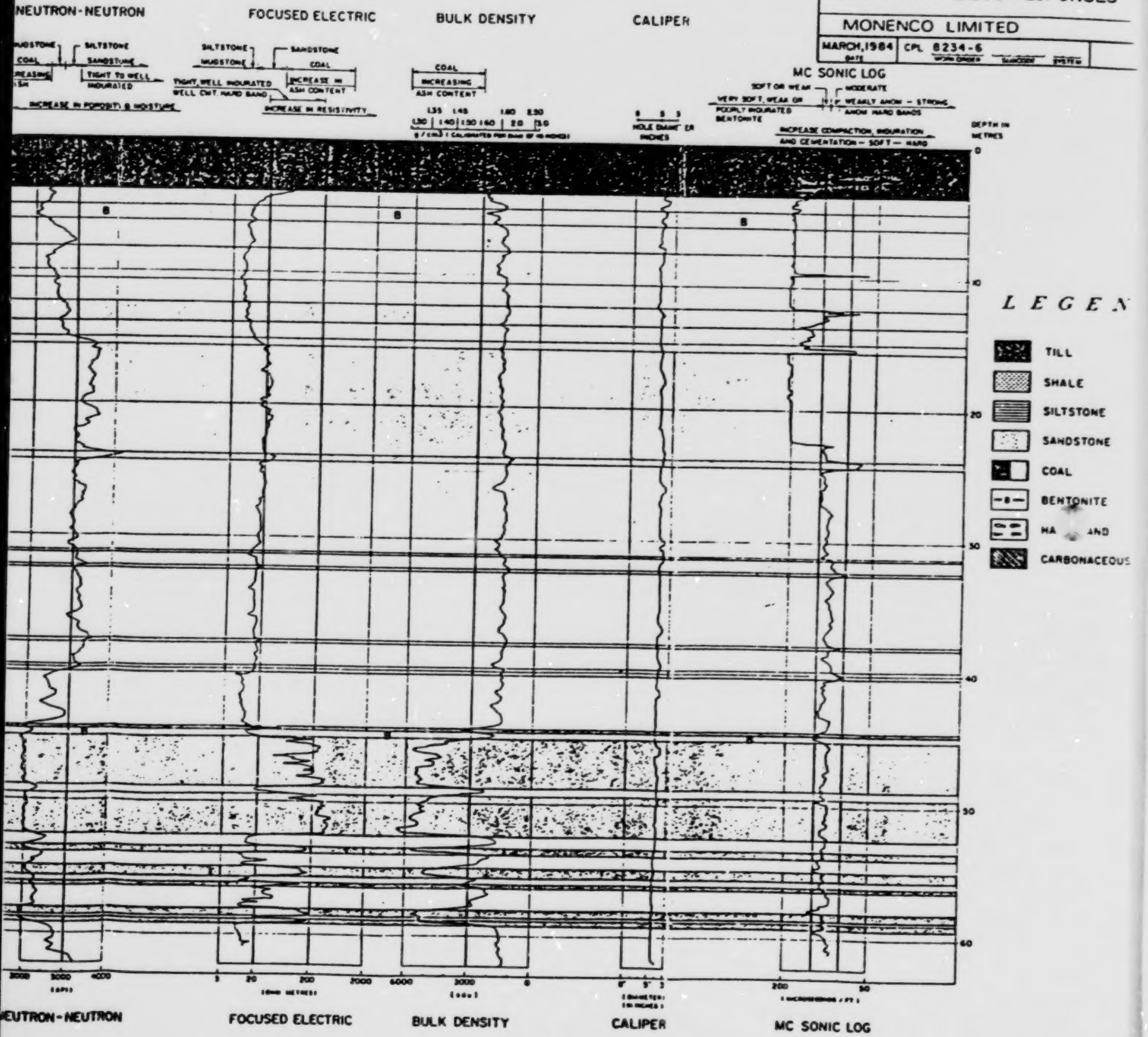
TRANSALTA UTILITIES

EXTENDED GEOLOGICAL MAPPING

TYPICAL BOREHOLE
GEOPHYSICAL LOG RESPONSES

MONENCO LIMITED

MARCH,1984 DATE	CPL 8234-6 WORK ORDER



ESPONSE OF SPECIFIC LOGS TO VARIOUS LITHOLOGIES AND ROCK CONDITIONS

FIGURE 6

TABLE 2

Highvale Mine - Summary of Satisfactory Correlations

Parameters Correlated	Equations Obtained	R	N
WC vs Gamma	$\mathrm{WC} = 0.234\ (\mathrm{Gamma}) - 8.284$	0.72	81
WC vs Density Log	$\mathrm{WC} = 141.86 - 57.0\ (\mathrm{DenLog})$	0.86	81
	$\mathrm{WC} = \log^{-1}\ [5.77 - 2.12\ (\mathrm{DenLog})]$	0.87	81
WC vs Neutron	$\mathrm{WC} = 58.65 - 0.0192\ (\mathrm{Neut})$	0.80	81
	$\mathrm{WC} = 367.19 - 105.1\ \log(\mathrm{Neut})$	0.82	81
	$\mathrm{WC} = 4.73 \times 10^{14}\ (\mathrm{Neut})^{4.065}$	0.86	81
	$\mathrm{WC} = \log^{-1}\ [2.80 - 0.00076\ (\mathrm{Neut})]$	0.87	81
WC vs Long Sonic	$\mathrm{WC} = 0.08\ (\mathrm{Sonic}) - 20.58$	0.66	81
WC vs Resistivity	$\mathrm{WC} = 22.73 - 0.52\ (\mathrm{Resist})$	0.58	81
Bulk Density vs Gamma	$\mathrm{BDen} = 2634 - 3.81\ (\mathrm{Gamma})$	0.60	94
	$\mathrm{BDen} = 4727\ (\mathrm{Gamma})^{-0.164}$	0.59	94
Bulk Density vs Neutron	$\mathrm{BDen} = 1370 + 0.388\ (\mathrm{Neut})$	0.79	94
	$\mathrm{BDen} = 104.1\ (\mathrm{Neut})^{0.4}$	0.78	94
	$\mathrm{BDen} = 2076\ \log(\mathrm{Neut}) - 4704$	0.79	94
	$\mathrm{BDen} = \log^{-1}\ [3.182 + 0.000074\ (\mathrm{Neut})]$	0.78	94
Bulk Density vs Long Sonic	$\mathrm{BDen} = 3023 - 1.76\ (\mathrm{Sonic})$	0.69	94
	$\mathrm{BDen} = 1.55 \times 10^{4}\ (\mathrm{Sonic})^{-0.32}$	0.69	94
Bulk Density vs Resistivity	$\mathrm{BDen} = 2076 + 11.2\ (\mathrm{Resist})$	0.59	94
	$\mathrm{BDen} = 1728\ (\mathrm{Resist})^{0.10}$	0.65	94
Bulk Density vs Density Log	$\mathrm{BDen} = 1190\ (\mathrm{DenLog}) - 403$	0.84	108
Qu vs Neutron	$\mathrm{Qu} = 0.038\ (\mathrm{Neut}) - 79.8$	0.69	58
	$\mathrm{Qu} = 248\ \log(\mathrm{Neut}) - 827$	0.71	58
	$\mathrm{Qu} = 1.5 \times 10^{-28}\ (\mathrm{Neut})^{8.4}$	0.68	58
Qu vs (Neutron x Density Log)	$\mathrm{Qu} = 0.02\ (\mathrm{Neut} \times \mathrm{DenLog}) - 85.6$	0.78	58
	$\mathrm{Qu} = \log^{-1}\ [6.2\ (\mathrm{Neut} \times \mathrm{DenLog}) - 13.7]$	0.85	58
	$\mathrm{Qu} = 6.3 \times 10^{-29}\ (\mathrm{Neut} \times \mathrm{DenLog})^{7.7}$	0.77	58
Qu vs Long Sonic	$\mathrm{Qu} = 224 - 0.82\ (\mathrm{Sonic}) + 0.00073\ (\mathrm{Sonic})^{2}$	0.91	58
	$\mathrm{Qu} = \log^{-1}\ (3.73 - 0.0075\ (\mathrm{Sonic}))$	0.80	58

Legend:

WC = Natural moisture content, %
DenLog = Density Log, Mg/c.m.
Bulk Density = Insitu density from laboratory test, kg/c.m.
Sonic = Average Long Sonic Transit Time, micro-sec/m
Qu = Uniaxial compressive strength, MPa
R = coefficient of correlation
N = no. of observations

TABLE 3

Highvale Mine - Summary of Geophysical Parameter Cross-Plots

Parameters Correlated	Equations Obtained	R	N
Density Log & Neutron	Neut = 2166 (DenLog) - 2554	0.82	105
	Neut = $\log^{-1}$ [0.416 (DenLog) + 2.42]	0.84	105
Density Log & Gamma	Gamma = 403.5 - 136.6 (DenLog)	0.66	105
Density Log & Long Sonic	Sonic = 1184 - 337 (DenLog)	0.68	105
	Sonic = $\log^{-1}$ [3.435 - 0.36 (DenLog)]	0.68	105
	Sonic = 1734 $(\text{DenLog})^{-1.76}$	0.66	105
	Sonic = 1003 - 1642 log(DenLog)	0.66	105
Density Log & Resistivity	Resist = 32.6 (DenLog) - 56.2	0.49	105
	Resist = $\log^{-1}$ [0.81 (DenLog) - 0.66]	0.50	105
	Resist = 0.62 $(\text{DenLog})^{3.89}$	0.48	105
	Resist = 157 log(DenLog) - 38	0.47	105
Resistivity & Neutron	Neut = 1769 + 30.9 (Resist)	0.78	105
	Neut = 1202 $(\text{Resist})^{0.24}$	0.78	105
	Neut = 813 + 1282 log(Resist)	0.79	105
Resistivity & Gamma	Gamma = 131 - 2.0 (Resist)	0.63	105
Neutron & Gamma	Neut = 3284.5 - 10.17 (Gamma)	0.80	105
	Neut = 1.72×10^4 $(\text{Gamma})^{-0.45}$	0.84	105
Long Sonic & Neutron	Sonic = 1.78×10^5 $(\text{Neut})^{-0.78}$	0.73	105
Long Sonic & Resistivity	Sonic = 7.2×10^2 $(\text{Resist})^{-0.2}$	0.62	105

For Legend see Table 2

To evaluate individual relationships paired, correlations were tentatively classified according to the R value obtained from the regression analysis as follows:

R Value	Correlation Rating
0.9+	very good
0.8 - 0.9	good
0.7 - 0.8	fair
0.6 - 0.7	poor
less than 0.6	unsatisfactory

The relationships in Table 2 which exhibit R values greater than 0.8 are deemed potentially useful in determining geotechnical parameters from the respective geophysical logs values. Those logs which appear most useful are the Neutron, Density and Sonic logs. With an R value of 0.87, the natural water content of a geologic formation can be predicted from the Neutron and Density logs by the following expressions:

$$WC = \log^{-1}[5.77 - 2.12(\text{DENLOG})] \qquad \ldots\ldots\ldots\ldots\ldots(1)$$

$$WC = \log^{-1}[2.80 - 0.00076(\text{NEUT})] \qquad \ldots\ldots\ldots\ldots\ldots(2)$$

Similarly, expressions for the Bulk Density (R = 0.84) and uniaxial compressive strength (R = 0.85 to 0.91) are as follows:

$$\text{Bulk Density} = 1190(\text{DENLOG}) - 403 \qquad \ldots\ldots\ldots\ldots\ldots(3)$$

$$Qu = 224 - 0.82(\text{SONIC}) + 0.00073(\text{SONIC})^2 \qquad \ldots\ldots\ldots\ldots\ldots(4)$$

$$Qu = \log^{-1}[6.2(\text{NEUT} \times \text{DENLOG}) - 13.7] \qquad \ldots\ldots\ldots\ldots\ldots(5)$$

Attempts to relate various Atterberg Limits test parameters to geophysical log values were thus notably unsuccessful as illustrated in Table 4. Correlations involving the Liquid Limit (LL), Plasticity Index (PI) and Relative Consistency (Cr) all exhibited correlation coefficients (R) less than 0.60.

A foreknowledge of the above geotechnical parameters from a feasibility exploration in which only geophysical logging of the drill holes is carried out would be useful in selecting the best locations for geotechnical core sampling in subsequent drilling programs. Noncarbonaceous formations with high natural moisture or low density are indicative of weak materials which may jeopardize the stability of pitwall slopes or give rise to trafficability problems.

By relating sonic transit time of a given formation to the corresponding uniaxial compressive strengths, valuable information on the diggability characteristics of the overburden units can be obtained over a wide area of the mine. Practical use of this correlation is being considered (A. Hickinbotham, Personal Communications) to assess diggability in the selection of mining equipment for planning purposes. To determine whether universal relationships exist between selected geotechnical and geophysical parameters, or to improve specific correlations for a given site, it will be necessary to carry out further studies. Based on the work conducted on the Highvale data to date, it appears that better correlations may be realized if the following procedures are used:

TABLE 4

Highvale Mine - Unsatisfactory Correlations

Parameters Correlated	R	N
LL vs Gamma	0.42	52
LL vs logGamma	0.40	52
log LL vs Gamma	0.42	52
LL vs Neutron	0.31	52
LL vs logNeutron	0.30	52
logLL vs logNeutron	0.37	52
logLL vs Neutron	0.38	52
LL vs Density Log	0.59	52
LL vs logDensity Log	0.60	52
logLL vs Density Log	0.58	52
logLL vs logDensity Log	0.58	52
LL vs Long Sonic	0.07	52
LL vs Resistivity	0.03	52
PI vs logDensity Log	0.58	52
PI vs logNeutron	0.27	52
PI vs logGamma	0.37	52
PI vs Density Log	0.57	52
PI vs Neutron	0.28	52
PI vs Gamma	0.39	52
Cr vs Gamma	0.29	28
Cr vs Density Log	0.29	28
Cr vs Neutron	0.44	28
Cr vs Sonic	0.18	28
Cr vs Resistivity	0.34	28

Legend:

LL = liquid limit, %
Cr = relative consistency=(LL-W)/PI
W = water content, %
PI = plasticity index, %
Sonic = avg. long sonic transit time, micro-sec/m

Note:

All geophysical log values used were average values over the stratum thickness being considered.

- Pair combinations of parameters to enhance the correlation coefficient, e.g. from Table 2, Qu vs Neutron gives maximum R = 0.71 whereas Qu vs (Neutron x Density Log) increases R to 0.85.

- Include data from different sites in the parameter pairing, e.g. the Qu vs Sonic Travel Time relationship for Highvale data is comparable to that for Australian Mines (see Figure 7). Care must be taken to minimize the errors due to different equipment and calibration before incorporating the data.

- Evaluate individual lithologic units separately and possibly group according to depth to acertain effects of glaciation.

- By conducting appropriate analyses, determine the minimum number of observations required to ensure a given relationship is statistically significant, or conversely, establish the minimum acceptable coefficient of correlation required to adequately define a reliable correlation.

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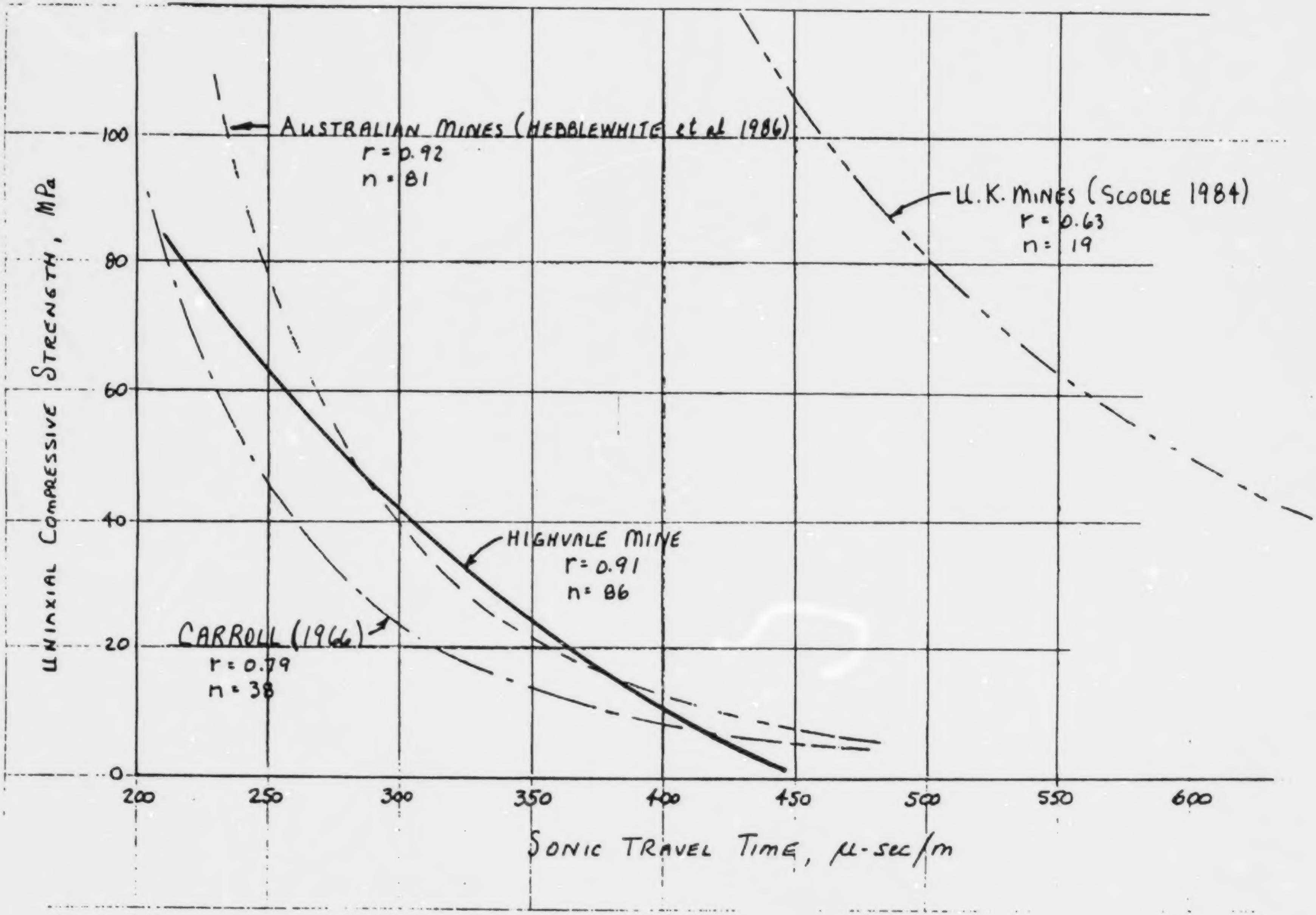


4. GEOTECHNICAL - OIL SANDS FORMATIONS

4.1 Data Search

The data compiled in this section of the study were from Syncrude Canada Ltd's two oil sands leases 17 and 22, located in the Athabasca Oil Sands area of Northeastern Alberta.

The data were selected after reviewing geotechnical and geophysical information that existed in different files or departments of the Syncrude organization. Much of these data were in hard copy form which could not be easily incorporated into this study.

Two groups of geotechnical and geophysical data were selected. These are designated as:

(1) Grainsize 01 to 21
(2) Holes 01 to 12.

4.2 Methodology

In the First Group Data file, geophysical log values were compared to the grain size fraction. These were both downloaded from a mainframe data base onto a personal computer Lotus 1-2-3 spreadsheet file. The geophysical logs were digitized at ten centimetre intervals.

In the Second Group Data file, the geophysical log values were also downloaded from a mainframe data base onto a personal computer Lotus 1-2-3 spreadsheet file. The geotechnical test intervals were manually entered into the Lotus file at the correct depths. In the case of the resistivity, density, and neutron logs some test interval depths were corrected. This type of correction occurred when the test interval was located near a lithologic contact resulting in large changes in geophysical log values. Because of limits to the resolution capability of tools, the geophysical response is gradational, increasing as the contact is approached. Thus, geophysical response values close to such a contact are not representative of either lithologic type and have been eliminated.

The geotechnical and geophysical data were supplied by Syncrude on floppy discs in the Lotus 1-2-3 format. Terracon rearranged these data to create a series of files. Each file contained hole number, measurement depth, one geophysical log and one geotechnical parameter. A number of successive files were created and each geotechnical parameter was paired with the appropriate log parameter.

The statistical regressions employed the following geotechnial parameters: undrained shear strength, liquid limit, plasticity index, moisture content and grain size data. The geophysical log data were supplied in digitized format and included data from the gamma, density, resistivity and neutron logs.

Certain data populations were sufficiently large to subdivide the correlation fields into sub-units of the Clearwater Formation. From eldest to youngest these members have been designated as Kcw, Kca, Kcb and Kcc.

The grain size data were examined on the basis of four separate properties, namely: sand content, silt content, fines content and the slope of the grain size gradation curves. This slope was derived by subtracting the amount of material passing through the 2.8 micron sieve from the amount of material passing through the 62 micron sieve and dividing by the sieve size difference (59.2 microns). The geophysical parameters include gamma, resistivity, neutron-porosity and density-porosity.

4.3 Tests and Tools

The First Group of data were obtained from 21 core holes (GR 01 to 21) drilled with a rotary diamond drill rig using an HQ wireline core barrel.

Two hundred and nineteen grain size tests were completed in 21 core holes. The grain size data were analyzed using a Microtrac test instrument. Microtrac sizes which were recorded are: 150, 125, 88, 62, 44, 31, 22, 16, 11, 7.8, 5.5, 3.9, and 2.8 Microns. Of the two hundred and nineteen samples only three or four contained coarser fractions with a grain size greater than one hundred and fifty microns. The coarser fraction was not analyzed.

The Second Group of data were selected from different drilling programs covering the period between February 1975 and December 1985. Samples for geotechnical tests from Hole 01 were obtained with a rotary rig using an HQ wireline core barrel. The remaining holes were drilled with a rotary rig using a Pitcher Barrel sampler and Shelby tubes. The testing completed in the twelve holes (Holes 01 to 12) is summarized in Table 5 and particulars of some of the tests are included below:

- Moisture Content ASTM D2216-71.
- Atterberg Limits, samples prepared with five minutes of blenderizing and one hour rest before testing, ASTM D2216-71.
- Clay Mineralogy (Montmorillonite, Chlorite, Illite and Kaolinite), the X-Ray Diffraction tests were performed with glyconated samples at the Alberta Research Council.

TABLE 5

GEOTECHNICAL TESTING
(HOLE 01 TO HOLE 12)

TEST	HOLE NUMBER 1	2	3	4	5	6	7	8	9	10	11	12	TOTAL # OF SAMPLES
Moisture Content	71	3	6	2	1	1		14					98
Atterberg Limits	62	3	7	2	1	1		12					88
Clay Mineralogy				2	7	4	3	1	2	6	9	21	55
Grain Size	61		1					1					63
(Sand, silt, clay)													
Activity	61												61
Bulk Density	10	2	8	2	1	1		10					34
Dry Density	10												10
Test Type		2	8	2	1	1		12					26
Failure at Max.													
(o'1-o'3)													
(% Strain)		2	7	2	1	1		10					23
(at Max O's)		1	3	2		1		6					13
(O'ol&C')			1	1									2
O'o&C' envelope													
B			1	1									2
qu (kPa)		1	4		1			4					10
Direct Shear													
O'peakenvelope			1					2					3
C'p (kPa)			1					2					3
O'res envelope			1					2					3
C'r (kPa)			1					2					3
Confining Pressure	17												17
Undrained Shear Strength (kPa)	17												17
Strain at Peak (S1-S3)	17												17

- Grain Size - the total percentage of clay, silt, and sand were reported using the Quick Hydro Meter Tests. ASTM procedures were followed with the exception that a three per cent solution of H_2O_2 (hydrogen peroxide) was used to soak the sample until fizzing has stopped. The sample was then blenderized for two minutes then added to 125 ml of a four per cent solution of Calgon. The remaining liquid volume for the hydrometer test was made up using distilled water.
- Unconfined compressive strength ASTM D2166-66.

The geophysical logging for the First Group (Grain Size 01 to 21) was performed by GEOLOG CANADA LTD. and various contractors for the other 12 holes.

The geophysical logging tool specifications for the adjacent holes are summarized on Table 6. The geophysical signatures and lithologic characteristics of the Clearwater Formation are shown in Figure 8.

4.4 Correlations

A total of 55 correlation plots have been generated with the available data. These are listed in Table 7. These graphs include both linear and semi-logarithmic plots for each parametric pairing. The correlation graph plots are presented in Appendix IV.

4.5 Discussion

4.5.1 Moisture Content

The moisture content is the ratio of the weight of water to the weight of dry soil/rock. This parameter was correlated against three geophysical logs, Bulk Density, Neutron Porosity and Resistivity. Correlation coefficient values are summarized as follows.

Log Type	Linear Plot	Semi-Logarithmic Plot
Density	-0.77	-0.76
Neutron-Porosity	+0.52	--
Resistivity	+0.25	+0.26

The negative R values indicate inverse relationships. The results show that for these sediments a reasonable inverse correlation has been obtained for the moisture content density correlation curve and that moisture estimates made from density curve provide reasonable approximations of the moisture values.

TABLE 6

GEOPHYSICAL LOGGING TOOL SPECIFICATIONS

HOLE 01 TO HOLE 12

HOLE NUMBER	LOGGING COMPANY	DATE	GEOPHYSICAL LOGGING TOOL SPECIFICATIONS														
				RESISTIVITY			GAMMA RAY			DENSITY			NEUTRON			CALIPER	
			SONDE	SPEED	TC SEC	SONDE	SPEED	TC SEC	SONDE	SPEED	TC SEC	SONDE	SPEED	TC SEC	SONDE	SPEED	TC SEC
01	BPB	Dec/1985	232	9	0.3	118	9	1	118	9	0.3	515	9	1	118	9	0.3
02	Schlumberger	Feb/1978	117 Laterolog-8	30	2	PGT CNT	30	2	PGT CNT	30	2	PGT CNT	30	2	PGT CNT	30	2
03	Schlumberger	Feb/1977	192 Laterolog-8	30	2	PGT-E, CNT-A	30	2	PGT-E, CNT-A	30	2	PGT-E, CNT-A	30	2	PGT-E, CNT-A	30	2
04	Schlumberger	Feb/1978	117 Laterolog-8	30	2	PGT-H, CNT-A	30	2	PGT-H, CNT-A	30	2	PGT-H, CNT-A	30	2	PGT-H, CNT-A	30	2
05	Schlumberger	Feb/1978	117 Laterolog-8	30	2	PGT-H, CNT-A	30	2	PGT-H, CNT-A	30	2	PGT-H, CNT-A	30	2	PGT-H, CNT-A	30	2
06	Dresser Atlas	Mar/1975	1300 Laterolog	20	3	1305	20	3	2208	20	3	-	-	-	?	20	3
07	Schlumberger	Feb/1978	117 Laterolog-8	30	2	PGT-H, CNT-A	30	2	PGT-H, CNT-A	30	2	PGT-H, CNT-A	30	2	PGT-H, CNT-A	30	2
08	Schlumberger	Feb/1978	117 Laterolog-8	30	2	PGT-H, CNT-A	30	2	PGT-H, CNT-A	30	2	PGT-H, CNT-A	30	2	PGT-H, CNT-A	30	2
09	Schlumberger	Feb/1978	117 Laterolog-8	30	2	PGT-H, CNT-A	30	2	PGT-H, CNT-A	30	2	PGT-H, CNT-A	30	2	PGT-H, CNT-A	30	2
10	Dresser Atlas	Feb/1975	LSL 1300 Induction	20	3	1305	20	3	2208	20	3	-	-	-	?	20	3
11	Dresser Atlas	Feb/1975	LSL 1300 Induction	20	3	1305	20	3	2208	20	3	-	-	-	?	20	3
12	Schlumberger	Jan/1978	117 Laterolog-8	30	2	PGT-H, CNT-A	30	2	PGT-H, CNT-A	30	2	PGT-H, CNT-A	30	2	PGT-H, CNT-A	30	2
HOLES GR1 - 21																	
GEOLOG			6' Normal	12-		Sodium Oxide Crystal	12	2	Focussed* side Wall	12	0.5	Thermal American Beryllium	12	1	Single Arm	12	

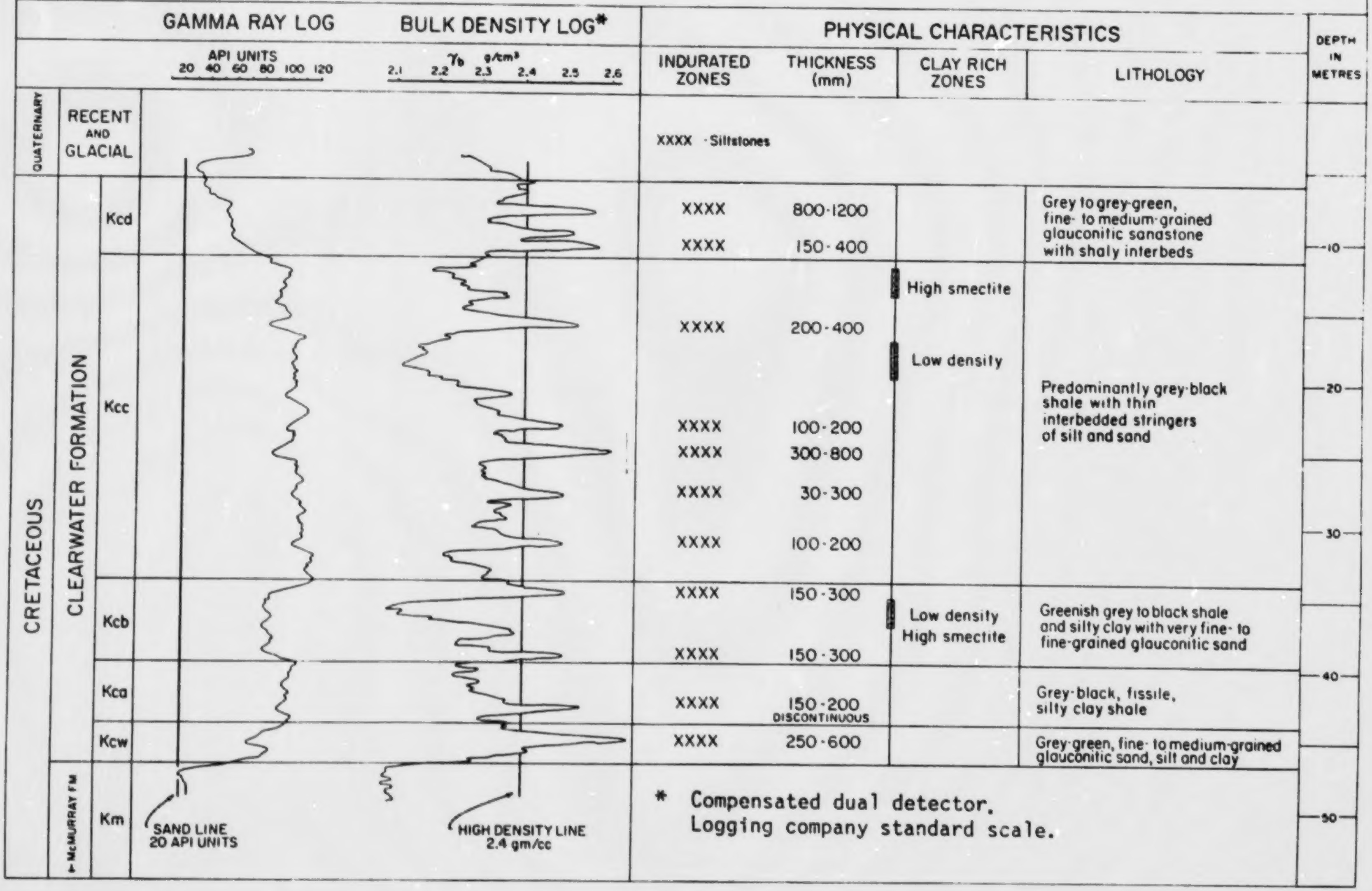
*Compensated single detector

Table 7

GEOTECHNICAL-GEOPHYSICAL CORRELATIONS

Parameters	R Coefficients		No. of Plots
	Linear	Semi Log	
Moisture Content vs Bulk Density	.77	.76	2
Moisture Content vs Neutron Porosity	.23	.30	2
Moisture Content vs Resistivity Log	.25	.26	2
Undrained Shear Strength vs Gamma	.36	.51	2
Undrained Shear Strength vs Bulk Density	.59	.70	2
Liquid Limit vs Gamma	.03	.05	2
Liquid Limit vs Bulk Density	.48	.47	2
Plasticity Index vs Gamma Log (Kcw)	.70	.71	2
Plasticity Index vs Gamma Log (Kca)	.35	.27	2
Plasticity Index vs Gamma Log (Kcb)	.13	.11	2
Plasticity Index vs Gamma Log (Kcc)	.44	.48	2
Plasticity Index vs Bulk Density	.44	.44	2
Fines Content vs Resistivity	.02	.02	2
Fines Content vs Neutron Porosity	.48	.49	2
Fines Content vs Density Porosity	.11	.07	2
Fines Content vs Gamma	.47	.54	2
Silt Content vs Resistivity	.11	.11	2
Silt Content vs Neutron Porosity	.09	.11	2
Silt Content vs Density Porosity	.005	.018	2
Silt Content vs Gamma			2
Sand Content vs Resistivity	.10	.04	2
Sand Content vs Neutron Porosity	.30	.32	2
Sand Content vs Density Porosity	.05	.03	2
Sand Content vs Gamma	.72	.72	2
Gradation Curve Slope vs Resistivity	.11	.13	2
Gradation Curve Slope vs Neutron Porosity	.09	.11	2
Gradation Curve Slope vs Density Porosity	.005	.018	2
Gradation Curve Slope vs Gamma	.62	.62	2
Total			56

GEOPHYSICAL SIGNATURES AND LITHOLOGIC CHARACTERISTICS OF THE CLEARWATER FORMATION



Unit	INDURATED ZONES	THICKNESS (mm)	CLAY RICH ZONES	LITHOLOGY
RECENT AND GLACIAL	XXXX · Siltstones			
Kcd	XXXX XXXX	800-1200 150-400		Grey to grey-green, fine- to medium-grained glauconitic sandstone with shaly interbeds
Kcc	XXXX XXXX XXXX XXXX XXXX	200-400 100-200 300-800 30-300 100-200	High smectite Low density	Predominantly grey-black shale with thin interbedded stringers of silt and sand
Kcb	XXXX XXXX	150-300 150-300	Low density High smectite	Greenish grey to black shale and silty clay with very fine- to fine-grained glauconitic sand
Kca	XXXX	150-200 DISCONTINUOUS		Grey-black, fissile, silty clay shale
Kcw	XXXX	250-600		Grey-green, fine- to medium-grained glauconitic sand, silt and clay

* Compensated dual detector.
Logging company standard scale.

FIGURE 8

The other R values are insufficiently strong to warrant further correlation attempts. The neutron-porosity log is affected by mineralogy, bitumen content (not generally present in the Clearwater Formation except in Kcw) and dissolved solids in the pore water as well as the amount of pore water. Consequently, the correlation is poor. The resistivity plot is affected by the dissolved solids content of the pore water as well as the mineralogy and the porosity. Variations in these parameters are probably causing the poor moisture content correlation. Removal of 14 high moisture values out of a total of 227 observations increases the R value for the Neutron Porosity versus moisture content from 0.23 to 0.52. Futher study of this data could improve the R value.

4.5.2 Undrained Shear Strength

The undrained shear strength (Qu) has been plotted against the gamma log on the theory that strength is inversely related to clay content. The correlation plots show a weak reverse relationship. A somewhat stronger correlation between Qu and the Density log is demonstrated. Here correlation coefficients of 0.54 and 0.72 have been obtained. The latter value was achieved for a semi-logarithmic plot. However, this correlation plot suffers from a small data population.

It is well known that undrained shear strength is a function of stress history for sediments which are overconsolidated such as the Clearwater Formation. Consequently, correlation of Qu with index properties are generally not very strong.

4.5.3 Liquid Limit (Atterberg Limit Parameter)

This parameter is an empirical test which arbitrarily measures the moisture content of clay rich soils at which a soil passes from a plastic state to a liquid state. The property is sensitive to the percentage of clay present as well as the clay mineralogy. In correlation attempts with the gamma log, both linear and semi-logarithmic plots show no correlation. The R values are 0.03 and 0.05 respectively. In addition, there is considerable data scatter. A very poor relationship is also obtained with the density log with an inverse relationship shown on the plot.

4.5.4 Plasticity Index (Atterberg Limit Parameter)

This property is defined as the difference in the liquid limit and the plastic limit. This property indicates the moisture content range over which a soil remains plastic.

Because of the amount of data available, plasticity values were correlated separately for each shale member of the Clearwater Formation against the Gamma Log. The following summary highlights the results.

Member	Linear Plot	Semi-Logarithmic Plot
Kcw	0.71	0.71
Kca	0.33	0.27
Kcb	0.13	0.11
Kcc	0.45	0.49

In all cases the R values are positive, but only the Kcw member provides a promising correlation coefficient. This result may have some ramification on all other correlation plots since it shows that successful correlation may be dependent upon the stratigraphic member. When plotted against the Density Porosity Log, the plasticity was shown to decrease as density increased. However, considerable scatter in the data renders weak correlation coefficients of -0.43 and -0.44 for the semi-logarithmic and linear plots, respectively.

4.5.5 Grains Size Correlations

Syncrude was able to provide a large quantity of particle size analysis data. While these parameters were originally defined as having a low priority by the Correlations Group, the availability of the data were seen as an opportunity to develop several correlations.

- Fines Content. The fines content (less than 0.002 mm per cent by weight) when plotted against the Resistivity, Neutron-Porosity, Density-Porosity and Gamma Logs produced generally poor correlations with a large scatter in the data plots. The highest R coefficient at 0.54 was obtained with the Gamma Log on a semi-logarithmic plot. However, all of the plots contain a large amount of scatter.

- Silt Content. The silt content is defined as the size range between 0.002 mm and 0.06 mm. The plots of this parameter against Resistivity, Neutron-Porosity, Density-Porosity and Gamma Logs are extremely poor and show no promise.

- Sand Content. The sand content is defined as the Size Range between 0.06 and 2.0 mm. Correlations were completed for the same geophysical logs as for the silt and fines fractions. A reasonable correlation (R = 0.72) was achieved for both linear and semi-logarithmic plots against the Gamma Log. As expected the Gamma Log value increases as the sand content decreases. While this plot produces a reasonable correlation coefficient the scatter of the data is still large and individual estimates of sand content inferred from a Gamma Log value could be in considerable error.

- Grain Size Uniformity. The slopes of the grain size curves, as a quantitative value representing the uniformity of material, were calculated and then plotted against the four major geophysical logs with Gamma Log providing correlation coefficients of -0.62 and +0.62 values for the linear and semi-logarithmic plots. The semi-logarithmic plot shows a relatively small amount of data scatter. The curve appears to offer promise for futher refinement with additional data.

4.5.6 General

The approach followed in the correlations discussed above was to use all of the data provided by Syncrude. Attempts were made to establish trends between geotechnical parameters and the various geophysical logging tools. Some trends were established between Qu and Density Log, moisture content and Neutron Porosity, Kcw and Density, fines content and Gamma Log and between sand content and the Gamma Log. All of these correlations showed a wide scatter of data and low R values. Additional studies are required to cull data with the purpose of improving the correlations.

5. HYDROGEOLOGICAL - COAL FORMATIONS

5.1 Data Search

Alberta Research Council (ARC) conducted the evaluation of hydrogeologic and geophysical log data. The initial task assigned to ARC was to determine the relationship between hydrogeological parameters and geophysical log data using existing data. This task was expanded during the study to include analysis of a similar data set supplied by TransAlta Utilities Corporation (TransAlta).

The ARC data were selected from a recently completed program which studied the effects of open cast mining and reclamation on the groundwater environment in the Highvale Coal Mine and the Battle River Coal Mining regions. See Figure 2 in Section 2.3. Groundwater data was also selected from ARC's Highwall Stability study at Highvale Mine in 1983. Additional data were provided by TransAlta from investigations at the Highvale Mine, 1983 to 1986. Geophysical logs and in most cases lithologs were available for the boreholes.

Data from the Highvale Mine came from Upper Cretaceous to Lower Tertiary age sediments of the Ardley coal zone that belong to the Lower Paskapoo Formation. The coal resources of the Battle River Mining area come from Upper Cretaceous Age sediments of the Lower Horseshoe Canyon Formation. See Figure 4 in Section 2.3.

5.1.1 Hydrogeologic Parameters and Data

The ARC review of the records revealed the following data:

Parameter	Number of Measurements
Hydraulic conductivity (K)	84
Water table (saturation)	33
Fluid conductivity (chemistry, salinity, T.D.S.)	300
Pore pressure	135

Initially, correlations were to be carried out on each of these parameters. However, retrieval and organizing of all the required data into a usable form proved to be a more difficult and time consuming task than anticipated. Therefore, the evaluation and correlations attempted in this study focussed on one parameter which was judged to be the most important from the available data, the hydraulic conductivity (K). A total of 45 hydraulic conductivity values were selected in the correlations and are shown in Table 8.

Table 8 Hydrogeologic and geophysical log data used for hydrogeologic evaluation.

	SCREENED INTERVAL		GEOPHYSICAL LOGS VALUES											HYDRAULIC CONDUCTIVITY	
Lithology	Hole #	Depth m	FE ohm-m	Log FE ohm-m	Resistivy relat. scale	Dual Neutron snu	Density adu	Density gm/cc	Sonic microsec/ft	Velocity m/sec	Gamma API	SP	Caliper inches	K m/sec	Log K m/sec
COAL															
- ARC -															
Seam 6	CHV83-1	50.8-51.8	88.82	1.84			4021.58	1.48	138.48	2201.09	52.85		4.91	3.00E-09	-8.52
Seam 6	CHV83-4	41.0-42.0	82.11	1.72			4046.80	1.47	134.73	2262.35	59.36		4.51	8.00E-10	-9.10
Seam 6	CHV83-8	40.5-41.5	79.18	1.80			3789.67	1.51	136.90	2226.44	54.73		5.30	2.00E-10	-9.70
Seam 6	CHV83-10	34.8-35.8	102.85	1.92			4100.11	1.48	142.15	2144.28	66.09		5.69	1.00E-10	-10.00
Seam 6	CHV83-11	58.2-59.2	127.64	2.02			4144.37	1.46	133.81	2277.87	57.18		4.37	5.20E-09	-8.28
Seam 1	HV17-3	13.7-16.7	463.97	2.61		43.45	4142.83	1.47			51.23		5.20	1.49E-06	-5.83
Seam 2	HV17-2	17.3-20.3	681.23	2.80		43.28	4381.28	1.45			47.35		5.20	3.12E-06	-5.51
Seam 6	HV17-1	26.6-27.6	312.13	2.44		40.23	4071.81	1.48			50.36		5.17	2.27E-06	-5.64
Seam 6	HV19-1	50.0-51.4	56.93	1.74			3716.76	1.53			62.93		5.55	3.13E-07	-6.51
Seam 1	HV23-4	37.0-38.8	148.14	1.78		52.09	3965.74	1.50			62.93		4.71	6.28E-08	-7.20
Seam 2	HV23-3	39.8-42.2	309.25	2.42		46.31	4812.02	1.40			35.64		5.21	4.32E-07	-6.37
Seam 6	HV23-2	47.0-48.0	81.19	1.77		51.12	4440.01	1.44			69.27		5.17	5.12E-08	-7.29
Upper Coal	BR8-3	15.8-19.5			190.33	32.45	4713.67	1.44			48.16	-0.32	5.40	2.50E-05	-4.60
Lower Coal	BR8-2	36.0-38.4			293.81	31.61	4517.97	1.47			46.60	-8.40	5.54	3.72E-06	-5.43
Upper Coal	BR14-3	29.4-32.4			200.39	36.80	2051.37	1.75			75.55	-17.87	4.54	2.74E-06	-5.56
Lower Coal	BR14-2	46.2-48.4			215.19	39.80	1970.84	1.81			70.43	-22.26	5.68	2.75E-07	-6.56
Upper Coal	BR15-3	21.0-22.0			289.67	31.28	5372.19	1.36			38.00	-9.18	5.76	8.49E-07	-6.07
Lower Coal	BR15-2	38.4-39.9			289.27	32.45	4557.25	1.47			46.75	5.06	5.09	1.48E-05	-4.83
-TAU -															
SEAM 2	HV83-409-2	49.1-50.1	313.32	2.50			4365.50	1.46	132.00	2309.09	36.66			7.0E-07	-6.15
SEAM 1	HV86-004-3	10.6-11.6	432.90	2.64			5188.80	1.38			16.80			4.4E-04	-3.36
SEAM 2	HV86-015-1	7.65-8.65	681.49	2.83			6120.40	1.31			20.36			2.7E-04	-3.57
SEAM 2	HV86-017-2	20.4-21.4	120.36	2.08		1505.90	5707.10	1.34	131.04	2326.01	15.83			1.2E-06	-5.92
SEAM 6	HV86-017-1	27.15-28.15	90.11	1.95		1527.60	4999.10	1.41	137.12	2222.87	60.47			5.5E-05	-4.26
SEAM 2	HV86-018-1	8.5-9.5	297.69	2.47			5773.80	1.34			24.66			3.0E-04	-3.52
SEAM 6/Mdst	HV86-018-2	14.15-15.15	20.12	1.30			2426.32	1.76			156.92			1.9E-04	-3.72
SEAM 2	HV86-019-1	43.0-44.0	79.74	1.90		1532.30	4266.00	1.48	134.60	2264.49	54.48			6.0E-07	-6.22
SEAM 2	HV86-020-1	43.15-44.15	372.22	2.57		1504.70	5447.10	1.36	129.21	2358.95	17.23			2.3E-07	-6.64
SEAM 2	HV86-400-1	30.0-31.0	304.70	2.48		1601.90	5339.10	1.37	131.07	2325.47	20.96			3.0E-09	-8.52
SEAM 2	HV86-404-1	37.45-38.45	314.34	2.50		1543.70	5339.30	1.37	129.83	2347.69	15.29			1.1E-06	-5.96
SEAM 2	HV86-405-1	9.3-10.3	344.46	2.54		1471.20	6359.30	1.29	173.00	1761.85	13.66			3.0E-04	-3.52
SEAM 6	HV86-405-2	16.8-17.8	132.42	2.12		1527.20	4849.80	1.43	131.50	2317.87	59.38			5.80E-05	-4.24
NON COAL															
- ARC -															
Siltstone	HV17-4	8.6-11.6	9.58	0.98		76.98	909.23	2.22			109.68		5.23	1.30E-05	-4.89
Siltstone	HV19-3	20.2-21.8	9.31	0.97			906.36	2.22			122.18		5.66	2.00E-06	-5.70
Sandstone	HV23-5	24.4-27.4	20.07	1.30		153.13	788.09	2.29			56.90		5.45	4.58E-07	-6.34
Delta Ss	BR8-1	37.6-43.9			115.22	93.89	1493.72	2.09			63.91	-3.36	5.45	9.27E-06	-5.03
Delta Ss	BR15-1	42.9-46.9			93.92	85.46	1725.12	2.01			72.83	-4.32	5.63	5.84E-07	-6.23
-TAU -															
SANDST	HV83-065-4	10.23-11.23	5.05	0.70			1139.00	2.11	159.70	1908.58	71.61			3.5E-06	-5.46
SANDST	HV86-019-3	11.15-13.15	22.91	1.36			1210.70	2.09			64.81			1.5E-07	-6.82
SANDST	HV86-400-3	19.50-20.50	20.99	1.32		1984.10	1208.30	2.09	160.39	1900.37	63.68			2.1E-07	-6.68
SANDST	HV86-404-2	25.5-26.50	14.29	1.16		2013.60	1203.60	2.13	136.65	2230.52	89.20			7.9E-07	-6.10
SAND/GRAV	HV83-411-4	16.68-17.68	19.23	1.28			738.90	2.37	128.10	2379.39	108.40			8.2E-06	-5.09
SAND/GRAV	HV83-413-4	7.25-8.25	20.13	1.30			2565.40	1.75	179.80	1695.22	107.70			3.1E-06	-5.51
SAND/GRAV	HV83-415-5	19.09-20.09	12.81	1.11			1651.20	1.98	147.30	2069.25	106.90			2.1E-05	-4.68
SAND	HV86-406-3	7.22-8.22					978.48	2.17			60.26			3.0E-08	-7.52
TILL	HV86-004-3	3.0-4.0	110.10	2.04			3111.10	1.62			249.20			6.9E-05	-4.16

The hydrogeologic data were collected from open piezometer stand pipes. Typical piezometer well completion consists of one screened interval within a sand or gravel pack per hole. A pelleted bentonite seal is placed above and below the sand pack. See Figure 9.

5.1.2 Geophysical Log Data

Suites of geophysical logs were available for the boreholes from which the hydraulic conductivity data were obtained. The number of logs used for each of the 3 data sets is summarized in Table 9. All the holes were geophysically logged by BPB Instruments (Canada) Ltd. between 1979 and 1986. Specifications of BPB geophysical tools are provided in Appendix II.

Table 9

GEOPHYSICAL LOGS USED FOR HYDROGEOLOGIC CORRELATIONS

DATA SET	GEOPHYSICAL LOGS							
	Gamma	Density	Caliper	Neutron	Focused Electric	Long Sonic	SP	Resistivity
ARC-Battle River (1979-1982)	3	3	3	3	-	-	3	3
ARC-HV Mine (1983)	8	8	8	2	7	5	-	-
TAU-HV Mine (1983-1986)	15	15	15	6	14	11	-	-
Total	26	26	26	11	21	16	3	3

NOTE: Density log is long spaced density in units SDU (BPB Standard Units).
Neutron log is dual spaced neutron in units SNU (BPB Standard Units).

The data from geophysical logs that were used in our analysis originated in hard copy form. Logs from selected boreholes were digitized using Logmate, ARC's log analysis computer system to provide numeric values for each log curve at 10 cm depth intervals.

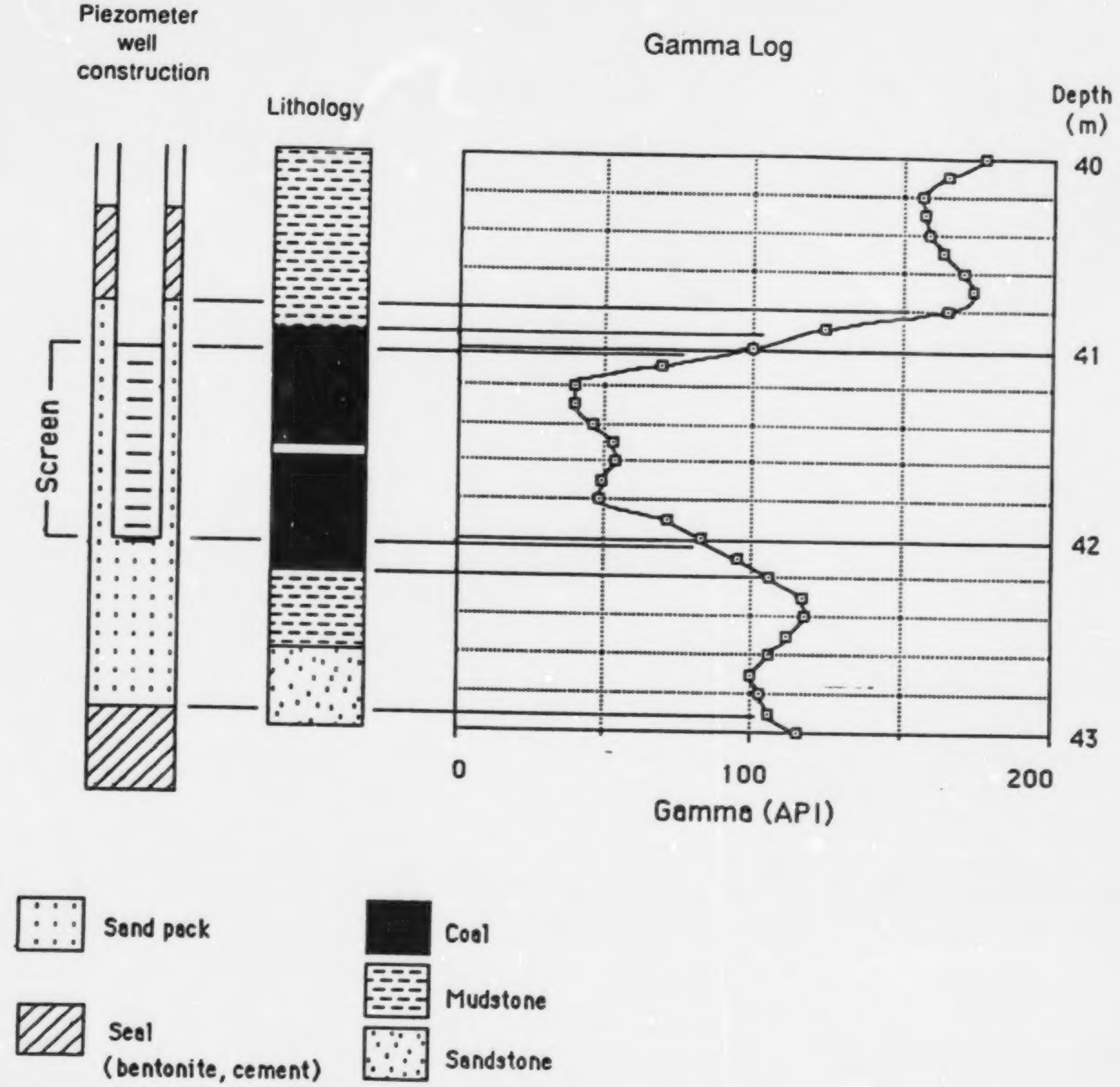


Figure 9. Relationship of piezometer well construction to stratigraphy and a geophysical log.

5.2 Methodology

The approach to the analysis of the data was to first make simple comparisons on a microcomputer of geophysical log values. The objective of this first comparison was to determine whether or not trends were evident and whether simple conclusions could be made.

Additional statistical computations were then carried out on the mainframe computer. The objective for this phase was to see if any trends could be recognized from the correlations. If so, these could be further investigated in the next phase of the project. Details of the data analysis procedures are presented in Appendix V.

For this study, the piezometer screen interval was chosen as the zone thickness of interest for correlation. The field of data was further narrowed down specifically to analyze measurements in coal. Several factors made it difficult to choose the correct geophysical log values that would be representative of the screened zone. These are discussed below in Section 5.2.1.

In order to maintain a degree of uniformity in choosing the geophysical log values, it was decided that all the geophysical log values that fell within the depth interval of the piezometer screen would be used to come up with an average value that would represent the zone (Figure 9). This method includes log values representing adjacent beds. No editing or filtering of the geophysical log data was used to account for noncoal values (i.e. parting, roof or floor rock). Future correlations should be undertaken using different criteria for selection of geophysical log values for the screened interval in coal.

5.2.1 Problems Encountered

Several obstacles and problems became apparent during data analysis. Some of these could not be easily resolved and may have a direct affect on the correlation results. These should be addressed in the next phase of the project work plan prior to collection of new data. Major problems identified are:

1) Access to Data. It became apparent very early in the data analysis that retrieving and compiling the necessary data would not be an easy task. The hydrogeologic data at ARC were in a computer data base, however, there was no direct link between the data files and the computer analysis programs. The data that were used in this study had to be entered manually. The ARC geophysical log data were even more difficult to access electronically. Data were available on cassette tapes in their field format. To get

the data into usable form for the analysis programs would have required several reformatting steps. This proved to be too costly. The alternative was to hand digitize a much smaller data set.

2) Proper Well Completion. Three choices were available in selecting the correct depth interval of the zone to be tested hydrogeologically. Should the screen interval, sand pack interval, or lithologic interval be used to represent the interval of the hydrogeologic zone? Figure 9 illustrates how each interval gives different ranges of gamma values for a coal seam that was targetted for testing. Ideally, the piezometer well should be completed so that screen and sand pack cover the exact depth interval of the seam. In practice, this is rarely the case and unrealistic to expect. In order to simplify our analysis, the screened interval was selected to represent the zone of interest from the geophysical log data.

3) Geophysical Log Curve Values. One of the biggest drawbacks with data from the geophysical logs is insufficient resolution. This factor poses a problem in determining which interval of geophysical log values should be used to calculate the average for the zone of interest.

The log curve values do not accurately represent the total thickness of a lithologic unit. Ideally, lithologic contacts would produce instantaneous changes in geophysical log responses. The inability of geophysical equipment to produce these instantaneous changes is due to the physical limitation of the downhole tool. Some logging tools have a better resolution than others. The Focussed Electric or Microresistivity Log has a resolution of about 10 cm compared to the Gamma Log which is in the order of 60 cm. However, with advanced recording equipment able to take a digital reading every centimetre, this means a minimum of 10 nonrepresentative values. Even though one tool has better resolution than the other, the problem remains about what to do with those values within the transition zone on the log that correspond to lithologic contacts. Depending on the volume of the data, these could be eliminated.

As an example (Figure 9), taking a coal seam that is 1.3 m thick with a gamma reading of about 50 API, what values from the log curve should be used to represent the true thickness of that seam? Several choices are available:

- Use all of the absolute geophysical log values over that 1.3 m interval.

- Block the log curve to give a value of 50 API over the entire 1.3 m interval.

- Use pure coal values only, i.e. filter out the partings values, and transition values at the contact with roof and floor rock.

Choosing the proper values to calculate the representative average of a zone can become a matter of interpretation. For this study, the actual geophysical log values were chosen, without any manipulation or filtering except for averaging, to represent the screened depth interval for correlations. Further analysis is required for a comparison of correlation results using the different criteria for geophysical log value selection to see which method is correct.

4) Calibration and Corrected Log Values. Calibration or corrections to log values to account for different variables needs to be studied. This does not necessarily apply to the actual calibration of the geophysical equipment itself. Other factors that may have an effect on correlation are: drilling fluid resistivity, drilling fluid density, hole diameter, and mineralogy.

The physical, chemical and electrical properties of the drilling fluid could have adverse effects on any quantitative analysis of the data. The effects of fluid conductivity is shown in an example of a corrected vs uncorrected log curve for the Focussed Electric log in Figure 10. This information should be requested from the logger and properly recorded in the field so that corrections can be incorporated into the log plot for subsequent data analysis.

5.3 Correlations

5.3.1 Simple Linear Regression Analysis

The first attempt at correlations for coal between hydraulic conductivity (K) and geophysical logs was carried out on a Macintosh microcomputer. Scatter plots were made of each geophysical parameter against the log of the hydraulic conductivity. The data used for the correlations were taken from Table 8. Two separate plots were made for each geophysical log, one using only values for coal and the other using values for both coal and noncoal material. The noncoal data included values for sandstone, siltstone, mudstone, till, sand and gravel. The graphs are presented in Appendix V. A simple regression fit has been applied to the data in the graphs which shows the equation and the 'best fit' line through the data points. The results are summarized in Table 10.

Initial observations in this study suggest that there is a low correlation between hydraulic conductivity and the geophysical logs. Trends may not have been detected because of the small number of data points used for many of the plots. Statistically, additional data are required to confirm the results.

There appears to be a lithologic influence to the plots. A comparison of the coal to noncoal graphs for several correlations show that two fields of data points are present. This is illustrated in the plots of the log of hydraulic conductivity against density for both coal, and coal and noncoal values (Figure 11). This suggests that all the data should not be grouped together for correlation because the rules for one lithology may not necessarily apply to the other. Each field of data should be interpreted separately. Additional correlations should be run with sandstone and mudstone data sets to see if they occupy separate fields within the scatter plots.

Observations of the graphs show that for coal, the neutron porosity plots appear to have the best correlation with hydraulic conductivity (Figure 12). The graphs show that as the neutron counts increase, hydraulic conductivity decreases (R = 0.79 and 0.74 for ARC and TransAlta respectively).

Table 10 Summary of hydrogeologic correlations attempted in first pass of analysis.

Correlation	Equation	R Value	n
Log K vs Gamma (coal)	Log K = -4.5188 - 0.036 Gamma	.39	30
Log K vs Gamma (coal & noncoal)	Log K = -6.9778 + 0.013 Gamma	.69	44
Log k vs Log FE (coal)	Log K = -12.8662 + 2.9047 Log FE	.48	20
Log K vs Log FE (coal & noncoal)	Log K = -6.2077 + 0.5077 Log FE	.20	31
Log K vs Density (coal)	Log K = 15.7357 - 15.3532 Density	.52	28
Log K vs Density (coal & noncoal)	Log K = -2.2085 - 1.6915 Density	.36	42
Log K vs Sonic (coal)	Log K = 27.329 - 0.2576 Sonic	.50	13
Log K vs Sonic (coal & noncoal)	Log K = -4.3298 - 0.0083 Sonic	.22	19
Log K vs NN (ARC coal)	Log K = -2.3264 - 0.0894 NN	.79	12
Log K vs NN (ARC coal & noncoal)	Log K = -4.199 - 0.0139 NN	.63	16
Log K vs NN (TAU coal)	Log K = 42.2788 - 0.0314 NN	.74	8

Where: Log K = log of hydraulic conductivity
Log FE = log of Focussed Resistivity
NN = Dual Spaced Neutron (Porosity)
R = correlation coefficient
n = number of samples
Density is bulk density measured in grams/cc

Correlation graphs are presented in Appendix 10.4

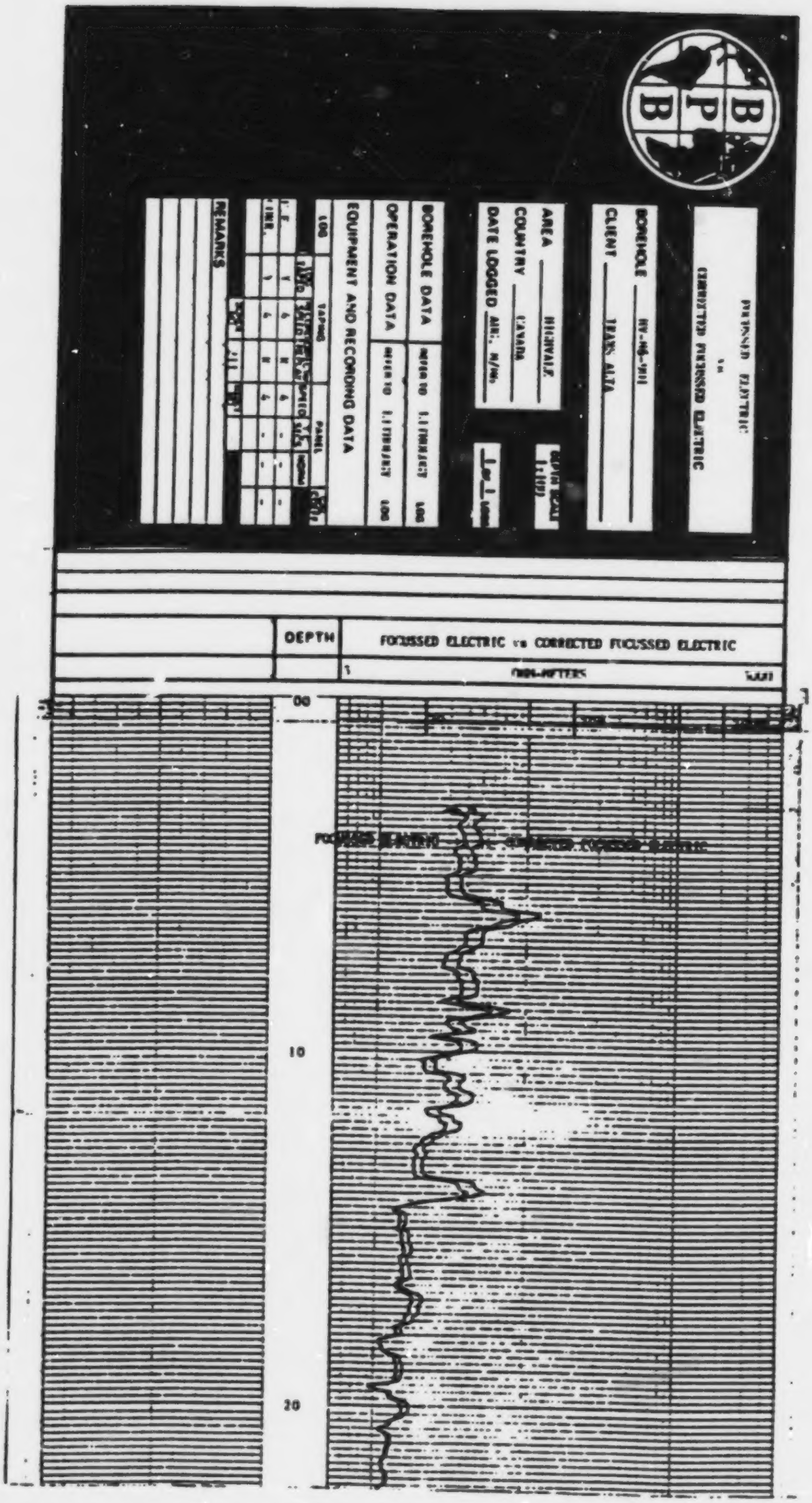
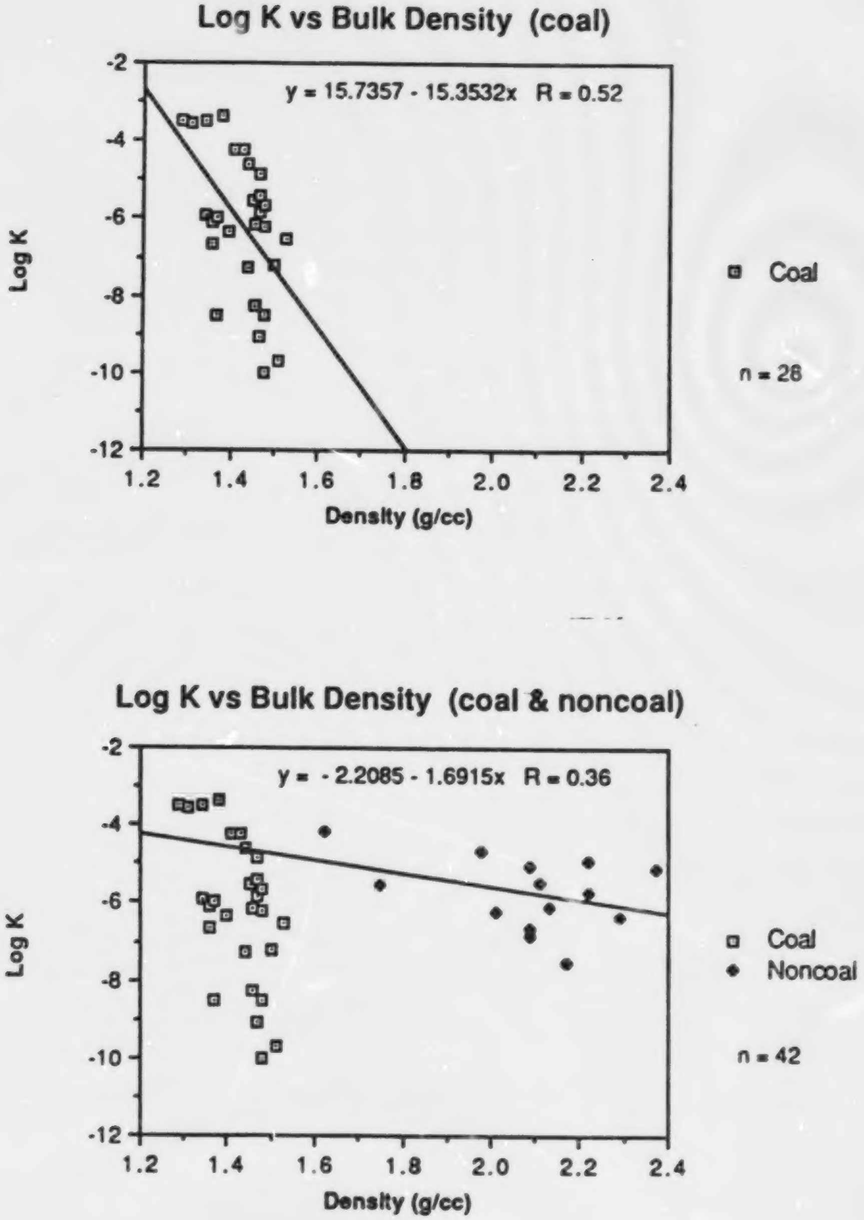
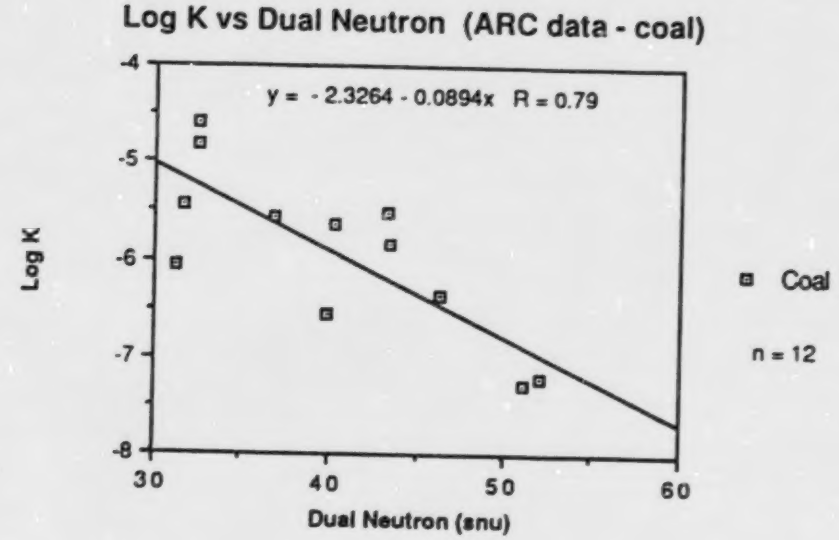


Figure 10: Example of borehole fluid correction for focussed electric log.

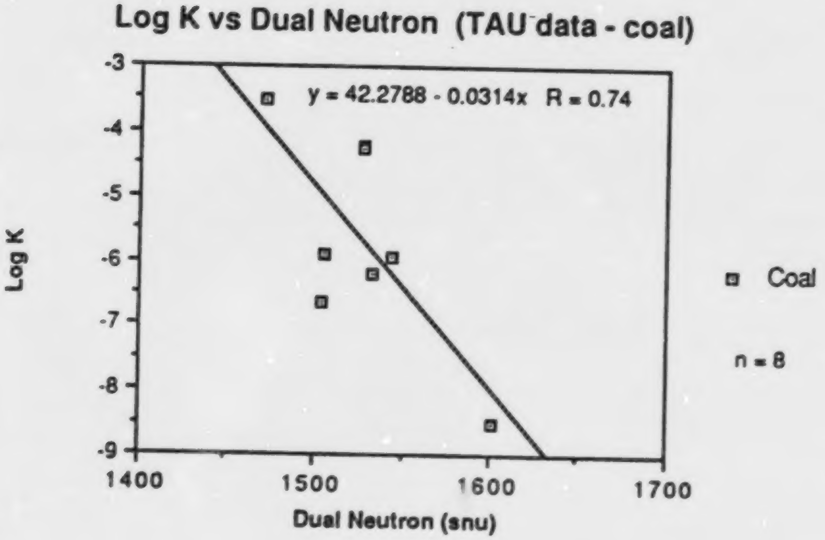

Log K vs Bulk Density (coal)

Log K vs Bulk Density (coal & noncoal)

Figure 11 Scatter plot, Log K vs Bulk Density.



Log K vs Dual Neutron (ARC data - coal)



Log K vs Dual Neutron (TAU data - coal)

Figure 12 Scatter plot, Log K vs Dual Spaced Neutron

5.3.2 Multiple Regression Analyses

A second stage of correlations was performed on the mainframe computer with a more sophisticated statistical program. This program allowed for a more rigorous analyses. These included significance tests of the relationships and of the parameters decribing the relationships. The following discussion contains several references to statistical measures of significance These measures are based on statistical theories beyond the scope of this report. Small probability values are indicative of greater significance. The adjusted R^2 is an estimate of the correlation between measured values and values estimated by the regression equation.

The first step in studying the relationship between geophysical logs and hydraulic conductivity values for coal was to conduct simple linear regression (SLR) analysis of each geophysical parameter against the log of the hydraulic conductivity (Table 11). Three geophysical parameters displayed relationships with hydraulic conductivity that are significant at the 5% level or better, (1) both the original values and logarithm of the focused electric log, (2) density (sdu) and, (3) natural gamma (Table 12). Even the best model, the log focused electric log, has an adjusted R^2 value of only 0.3413. Thus, it is evident that most of the variation in hydraulic conductivity is unrelated to variation in the geophysical logs. From these SLR analyses, the neutron log and calculated bulk density values have a limited relationship to log hydraulic conductivity. F-values are significant at the 8.78% and 6.79% levels respectively (Table 11). The sonic log displays essentially no relationship with the log hydraulic conductivity (Table 11).

Multiple regression models were evaluated to determine whether any combination of geophysical logs might be more strongly related to the log of hydraulic conductivity than were the individual logs. Four 2-parameter and four 3-parameter models were calculated.

The highest values of adjusted R^2 were found with three models that combined the logarithm of the focused electric log successively with standard density units, bulk density, and natural gamma (Table 12). The best of these models, the standard density units combined with log of focused electric, showed slightly more than half the variability of the hydraulic conductivity. This was also the only model that had at least one of the coefficients better than the 5% level.

The two parameter model involving gamma and density was the only model that could utilize all 28 of the samples in the data set (Table 12). This model had an adjusted R^2 of only 0.212, and an F-value of 4.631, which is significant at the 1.95% level. The t-value of the coefficient for the gamma ray log value is -2.251, which is significantly different from zero at the 0.0334 level. However, the coefficient for the density value is significantly different from zero only at the 0.8257 level.

TABLE 11 SUMMARY OF LINEAR REGRESSION MODELS RELATING LOG HYDRAULIC CONDUCTIVITY TO GEOPHYSICAL LOG PARAMETERS.

					ADJRSQ	FVALUE	PROB>F	N
LOGK =	-15.1714	+	4.138981 T = 3.048 PROB. OF T = 0.0081	LOG FE	0.3413	9.291	0.0081	17
LOGK =	-3.72369	-	0.0491047 -3.092 0.0047	GAMMA	0.2408	9.562	0.0047	28
LOGK =	-8.36273	+	0.0105303 2.453 0.0269	FE	0.2387	6.017	0.0269	17
LOGK =	-10.1116	+	0.000903 2.857 0.0083	DENSITY (SDU)	0.2097	8.164	0.0083	28
LOGK =	-5.92288	+	0.0005842 1.818 0.0878	NEUTRON	0.1194	3.306	0.0878	18
LOGK =	2.365785	-	5.78622 -1.905 0.0679	BULK DENSITY	0.0887	3.628	0.0679	28
LOGK =	-14.2764	+	0.0540413 0.922 0.3783	SONIC TRANSIT TIME	-0.0138	0.85	0.3783	12
LOGK =	0.526409	-	0.0033076 -0.75 0.4705	SONIC VELOCITY	-0.0414	0.563	0.4705	12

TABLE 12 SUMMARY OF MULTIPLE REGRESSION MODELS RELATING LOG HYDRAULIC CONDUCTIVITY TO GEOPHYSICAL LOG PARAMETERS.

											ADJRSQ	FVALUE	PROB>F	N
Two Parameter Models														
LOGK =	-16.44	+	0.8732	FE	+	0.002	DENSITY (SDU)				0.5198	9.66	0.0023	17
		T =	0.507			2.564								
		PROB. OF T =	0.62			0.023								
LOGK =	13.523	-	16.156	DENSITY	+	1.4652	LOG FE				0.4399	7.282	0.0068	17
			- 1.908			0.78								
			0.0772			0.4486								
LOGK =	-15.33	+	0.001	GAMMA	+	4.1933	LOG FE				0.2943	4.336	0.0342	17
			0.027			1.724								
			0.9786			0.1068								
LOGK =	-4.873	+	0.9132	DENSITY	-	0.0529	GAMMA				0.212	4.631	0.0195	28
			0.223			-2.251								
			0.8257			0.0334								
Three Parameter Models														
LOGK =	-2.345	+	0.1226	DENSITY	-	0.011	GAMMA	-	0.0784	NEUTRON	0.5201	4.974	0.031	12
		T =	0.062			-0.56			-2.51					
		PROB. OF T =	0.9522			0.597			0.0364					
LOGK =	18.288	-	23.34	DENSITY	+	0.0488	GAMMA	+	3.0088	LOG FE	0.4685	5.702	0.0102	17
			-2.364			1.325			1.387					
			0.0343			0.208			0.1889					
LOGK =	50.58	-	38.394	DENSITY	+	0.0453	GAMMA	-	0.0326	TRANSIT TIME	0.4467	3.96	0.0531	12
			-2.596			0.994			-0.638					
			0.0318			0.3495			0.5413					
LOGK =	26.791	-	25.06	DENSITY	+	0.0355	GAMMA	+	0.005	FE	0.426	4.958	0.0165	17
			-2.479			0.989			0.904					
			0.0277			0.3406			0.3826					

Four different three-parameter models were evaluated (Table 12). In these models the gamma and density values were combined successively with the sonic, focused electric, log of the focused electric and neutron logs. These models had adjusted R^2 values that range from 0.5201 for the neutron log (n=12) to 0.426 for the focused electric (n=17). In each model the coefficient of only one parameter is significantly different from zero (Table 12). For the models that included sonic transit time, log focused electric, and focused electric logs, only the density is significant, with t-values of -2.596 (significant at the 3.18% level with n=12), -2.364 (significant at the 3.43% level with n=17), and -2.479 (significant at the 2.77% level with a n=17), respectively. In the fourth model, only the coefficient for the neutron log is significant with a t-value of -2.51 (significant at the 3.64% level with n=12).

5.4 Discussion

On the basis of the preliminary regression analyses that have been carried out, there is little indication that the hydraulic conductivity of coal can be effectively estimated on the basis of geophysical log parameters. As is indicated by the low values of R^2 for all the models evaluated, most of the variability in hydraulic conductivity is not related to any individual log or any combination of logs included in this study.

The slight trends that exist are consistent with the theoretical relationships. Further work is required to refine the selection of hydraulic conductivity and the geophysical log values used in this analysis before it can be concluded that geophysics cannot be used to estimate hydraulic conductivity. Additional data sets should be obtained to confirm that this indication is not masked by insufficient data.

6. NEW GEOPHYSICAL PROBES

6.1 Selection of New Tools Based on Results of the Phase 2 Study

The results of the geotechnical correlation studies show that the gamma, sonic and gamma-gamma (density) geophysical probes have provided the most promising correlations. In the light of this information, it is suggested that enhancements to these tools and/or methods should be given careful consideration for the Phase 3 portion of the program. In keeping with the findings of the Phase 1 study on new tools, testing of a more sensitive gamma tool, a gamma spectral tool and a full waveform seismic tool are discussed in this chapter and recommended for consideration in Phase 3.

6.2 High Sensitivity Slim Line Gamma Probe

The gamma tool detects natural gamma radiation emanating from common radioactive isotopes including those of Potassium (K40), Thorium (Th232) and Uranium (U238). A high sensitivity tool (Geosource model T31 Gamma Ray Probe) has been developed especially for coal survey work to evaluate interseam and interply layers. It has a tool diameter of 4.2 cm and is easily integrated with logging systems of most other manufacturers. The tool can accommodate a variety of logging speeds. Because of its higher sensitivity, data derived from this tool may provide better correlations than the standard gamma tools.

6.3 Spectral Gamma Ray Probe

While this tool is not "new", it has not been used in coal and oil sands operations in the Western Plains. The probe's primary function is to resolve the relative amounts of Uranium, Thorium and Potassium radioactive isotopes. Removal of the uranium component from the total gamma ray curve allows a better estimate of the total clay volume. Similarily, specific ratios of Th/K, U/K and U/Th allows the determination of clay types (kaolinite, bentonite, illite, chlorite). These clay data can then be correlated with geotechnical data such as Atterberg Limit parameters and perhaps strength parameters.

6.4 Full Wave Form Sonic Probe

As shown in the correlation section of this report the P-wave sonic log has provided a good correlation with uniaxial compressive strength (Qu). With further refinement of the sonic technique it may be possible to provide improved correlation coefficients over those already obtained; the calculation of dynamic elastic moduli; and correlation with other geotechnical parameters such as effective shear strength, and tensile strength.

A compensated sonic sonde capable of providing a full wave form output together with time increments up and down in the borehole wall and a compensated time increment is available from BPB and other companies. Given the full wave form on a detailed (i.e. 10 cm) increment basis, it should be possible to identify the first shear wave arrival and transit time for this arrival. The shear wave data will provide elastic moduli and may be used as a correlative with the aforementioned geotechnical properties. In addition, tube wave amplitude related to hydraulic conductivity has been reported elsewhere.

6.5 Other Oil Field Tools with Potential Application

The Phase 1 report (Chapter 2) raised and revived a variety of downhole geophysical probes which have not been normally employed in coal field and oil sand evaluation programs. A total of fifteen possible methods were briefly reviewed in terms of their potential application to slim hole logging programs which are normally carried out for coal and oil sand reserve estimates.

A number of these tools are only available in large diameter configurations including:

a) Formation Microscanner
b) Measurement While Drilling (MWD)

These tools are expensive systems to operate, require large diameter holes and do not provide information that is unique and relevant to these studies. Consequently, test trials with this equipment are not recommended.

An Acoustic Televiewer is also available for logging 3 inch holes and may be of use in investigating the contribution of fractures to hydraulic conductivity.

6.6 Other New Slim Hole Tools

New slim hole tools which were included in the Phase 1 report (Chapter 7) are discussed very briefly:

Impluse Radar Methods. While very encouraging results have been obtained in hard rock environments, a review of detailed technical reports supplied by the Geological Swedish Company shows that water saturated materials with resistivities of 10 ohm metres or less allow very little penetration of the radar signal. Since most of the overburden lithologies of the coal and oil sand areas have relatively high conductivities it is highly unlikely that this method would not provide satisfactory results.

It should also be noted that surface radar systems, as opposed to borehole systems, have been tested in the oil sands. Poor penetration results were achieved.

Radio Imaging Method (RIM). This is an electromagnetic system based on a transmitter-receiver configuration from borehole to borehole. This method performs satisfactorily in coal fields with an electrical conductivity range of 5×10^{-4} to 5×10^{-1} mhos/m for coal and associated lithologies. However, the RIM methods have been developed to determine structural geology features such as faults, pinchouts, washouts and interseam splits. It has not been developed for specific geotechnical application. However, since these structural geology features often play a role in geotechnical mine design the method should be seriously considered for test trials in Phase 3 of this program.

An application of the method is foreseen in hydrogeology of oil sand leases. Delineation of the basal aquifer may be possible because of the conductivity contrasts between the overlying oil sand and the underlying limestone. Mean conductivities for these layers are estimated at 10^{-3}, 5×10^{-2} and 5×10^{-3} mhos/m for the oil sand, basal aquifer and limestone, respectively. This service is available from Stolar Inc. and the Southwest Research Institute.

Heat Pulse/Thermal Logging. The Geological Survey of Canada has offered the use of their thermal probe for measuring temperature gradients and computing lateral groundwater flows could be made available if sufficient notice is provided. Since the system is available free of charge and given the appropriate conditions (i.e. an area where low groundwater flow rates are expected as a result of mine dewatering or some other activitiy), it appears that this method should be tested.

Jessop (1987) has developed a method for estimating lateral flow by injection and thermal logging. This method is simple in principle but requires sophisticated mathematical modelling techniques to interpret the thermal data.

Low Frequency Pulse EM Probe. This system has been developed to locate and delineate sulphide ore deposits. It is designed to locate "off-hole" conductive zones in the presence of "in-hole" sulphides. The method operates with a horizontal transmitter loop at surface and a receiver probe in one or more boreholes which may be located inside or outside the transmitter loop. While the method functions well for host rocks with apparent resistivities in the range of 10 to 100 ohm metres, it is not certain that potential targets such as the basal aquifers in the oil sands would have sufficient resistivity contrast to provide "off-hole" geometries. Trial of the method in coal and oil sands should await test results in less resistive sedimentary host rock environments.

6.7 Prioritization of New Probe Tests

The costs involved in testing new borehole geophysical probes, especially oil field tools, is high. In addition, geotechnical data and/or hydrogeological data must also be obtained for each hole tested. This requirement adds to the cost.

Given the results of the geotechnical correlations and the preliminary values for the hydrogeology correlations it is suggested that further study be first focussed on certain standard logging tools including the gamma probe, the neutron sonde, the sonic tool and the gamma-gamma or density tool. Should additional funds be available, a second group of new tools which should be seriously considered are the Radio Imaging Method and Thermal Logging Tools for measuring lateral goundwater flow.

The gamma tool has two variants which are recommended including the high sensitivity tool from Geosource and the spectral gamma ray probe which is available from several oil field contractors. The former probe may provide correlation better than those already obtained because of its sensitivity. The latter probe provides individual response curves for the three common naturally occuring radioactive isotopes, (K, Th and U). Consequently, correlation with certain properties such as Atterberg Limits or undrained shear strengths may be improved. Clay mineral species groups may also be determined by the spectral tool.

The other probe recommended for futher test work is the full waveform sonic tool. It will provide data for elastic moduli computations as well as shear wave data for correlation with various strength values. Preliminary analysis of TransAlta's sonic data shows sufficiently good correlations with P-wave data and unconfined compressive strength that this method should be pursued. An alternative sonic probe (5 cm diameter) is available from the Southwest Research Institute in San Antonio, Texas. However, this system was especially developed for the U.S.G.S. and may require extended lead time to arrange for delivery to Canada. This P-wave and S-wave system has a receiver separation distance of 1 metre which may need to be changed so as not to limit the resolution of the tool.

Further efforts at correlating density log data with bulk density data should be focussed on obtaining standarized calibration of contractor's density tools at a single site (i.e. ISPG, Calgary) and collection of reliable density data. Application of the method to reworked materials (i.e. spoil and tailings) may also offer other opportunities for the density tool. New density tools with improved bed resolution would also be quite useful.

The last group of new tools which are recommended for consideration includes the hole to hole electromagnetic system. This system is designed to operate between pairs of vertical boreholes using pulsed radio frequency signals. The method was developed primarily to probe the continuity of lithologic materials between boreholes. As such it could have application in the coal fields for determining pinchouts, faults, etc. In the oil sand area of Fort McMurray, average conductivity data for oil sand, the basal aquifer and the underlying Devonian Limestone suggest that the method could be used to delineate the continuity and extent of the basal aquifer. The method is supported by at least two commerical sources; the Southwest Research Institue in San Antonio and Stolar Inc. of Albuquerque, New Mexico.

Thermal logging tools appear to have special applications in measuring lateral and vertical groundwater flows, especially where flow rates are below the threshold levels of the mechanical or impeller tool types. Trial applications of this method are warranted if the Geological Survey of Canada can make its equipment available. Also A.E. Hess of the USGS has developed a high sensitivity thermal flow meter to measure vertical flow in stem holes.

In summary, those Geophysical Probes which appear to have merit in either refinement of their application or new application testing are; high sensitivity gamma, spectral gamma, neutron, gamma-gamma (density), S-wave and P-wave sonic or full wave form sonic, hole to hole electromagnetic, thermal and acoustic televiewer.

7. CONCLUSIONS AND RECOMMENDATIONS

7.1 Geotechnical - Coal Formations

Based on the Highvale data studies, a number of correlations between geotechnical and geophysical parameters have been established with correlation coefficients greater than 0.8 (see Table 3).

The geophysical logs which give the best correlations are the Neutron, Density and Sonic Logs. Although more work is required to confirm the universality of some of these relationships, credibility for the uniaxial compressive strength vs sonic transit time relationship is strengthened by the good agreement with similar data from Australian Mines (see Figure 6).

For those relationships which exhibit correlation coefficients less than 0.8, enhancement of the correlation may be possible by increasing the number of observations, by pairing combinations of parameters, by considering individual lithologic units separately or by more rigorous scrutiny of the data to ensure consistency.

It is recommended that additional studies be carried out to confirm the correlations obtained and ascertain if additional relationships between geotechnical and geophysical parameters can be established. To this end, the following procedures should be considered:

- The minimum number of observations required to ensure a given relationship is statistically significant should be determined by appropriate analyses.
- The minimum value of the coefficient of correlation to adequately define a reliable correlation should be established.
- Additional geophysical data collected by Century Geophysical and available with TransAlta should be reformatted and included with the corresponding geotechnical data in future correlations.
- Data from different sites should also be included in future correlations. This includes data from Whitewood Mine, Syncrude Mine and available published data.
- Individual lithologic units should be evaluated separately. These should also be grouped according to depth to ascertain degree of glacio-tectonic disturbance.
- Combinations of parameters should be paired to obtain upgraded correlations if necessary.

- Only log data corresponding to the lithologic unit represented by the core or test should be selected.

- Non linear regression analysis should be attempted on this data.

- The variation in tool calibration and tool types from year to year and the effects on correlations should be evaluated.

- Attempts should be made to correlate geophysical logs with other geotechnical parameters such as effective shear strength and consolidation properties of mine spoil.

7.2 Geotechnical Oil Sands Formations

The paired parameters listed in Table 7, with R values greater than 0.7 suggest that correlations can be established between the following:

	R Coefficients	
	Linear	Semi-Logarithmic
Moisture Content vs Bulk Density	-0.77	-0.76
Undrained Shear Strength vs Gamma	--	0.72
Plasticity Index vs Gamma Log (Kcw only)	0.71	0.71
Sand Content vs Gamma Log	0.72	0.72

All of the above correlations have a wide scatter of data such that their use to estimate geotechnical parameters cannot be recommended in their present form.

A preliminary editing of the data (removing 14 out of 217 points) improved the correlation between Neutron Porosity vs moisture content from 0.23 to 0.52. This indicates that a detailed review and segregation of the data may significantly improve the correlations.

It is recommended that the four correlations above be examined with more data to determine whether stronger correlations can be established.

Additional correlations between geotechnical parameters such as effective shear strength, in situ densities for spoil and tailings and elastic moduli should be studied with the different geophysical logs.

7.3 Hyrogeologic - Coal

The conclusions are:

- Preliminary regression analyses carried out for this study indicates that hydraulic conductivity of coal cannot be effectively estimated on the basis of the geophysical log parameters tried.

- The poor relationship between hydraulic conductivity and geophysical logs may be due in part to the development of the data set used for analyses. A large number of assumptions and arbitrary decisions were made in selecting the data which could have had an influence on these results.

- Firm conclusions could not be drawn because of the small data set. This was especially true where data were combined into multiple parameter models for evaluation. There were simply too many missing values in the data set. More data is required to confirm results.

- The retrieval of existing data for hydrogeologic correlations proved to be a more difficult exercise than anticipated. Much of the data was in a form that could not be easily transfered to computer programs for analyses. This resulted in a much smaller usable data set than was originally hoped for.

- The weak relationships that are indicated suggest that the density, focussed electric and neutron logs give the most promising correlations. However, more analyses should be carried out and none of the logs should be discounted yet.

- From observations of the plots, there appears to be two fields of data groupings, one for the coal and the other for the noncoal. This suggests that each should be evaluated separately because the rules of the one may not necessarily apply to the other.

- In this study, the actual geophysical log values were chosen, without any manipulation or filtering except for averaging, to represent the screened depth interval for correlations. It is realized that these average log values reflect the influence of adjacent beds which may be of a different lithology. Greater care must be taken in future studies to ensure that geophysical log values are not averaged over different lithologic units.

Analysis of existing data sets should continue. The recommendations are:

- Additional analyses for coal should be carried out on existing data to further develop the data set used in the correlations. Greater refinement of both the hydraulic conductivity and geophysical log values needs to be explored.
- The data set used for correlations should be increased in size from existing data.
- Correlations should be attempted for sandstone and mudstone data sets.
- Priority should be given to completing correlations for hydraulic conductivity. However, if time permits, then correlations for the other hydrogeologic parameters, water table, pore pressure and fluid conductivity should be evaluated.

Future work is recommended.

- Tighter control is required for piezometer well completion. Existing hydrogeologic data shows that often the screen and sand pack were not properly aligned with the aquifer zone, making it difficult to determine the correct depth interval that should be used from the geophysical logs.
- During geophysical logging, measurements of the physical properties that might influence values on the logs should be taken. For example, drilling fluid conductivity, drilling fluid density, and hole diameter should be recorded so that corrections can be properly applied.
- For collection of new data, a full suite of geophysical logs should be run. Logs should include plots from both high bed resolution, shallow penetrating and low bed resolution, and deep penetrating tools.

8. REFERENCES

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APPENDIX 1

PROJECT ORGANIZATION AND MANAGEMENT

APPENDIX 1

1. Management Committee

The project is governed by a Management Committee that provides overall direction to the Hydrogeological and Geotechnical Committees conducting the study. This includes responsibility for project content and budget control, as well as responsibility for selection of the final technical and expert committee members.

The following individuals have been appointed to the Management Committee:

A. Hickinbotham, TransAlta Utilities Corporation (Chairman)
D. Scott, Civil Engineering Department, University of Alberta
E. Fraser, Suncor Inc.
N. Wade, Monenco Consultants Limited
G. Jenkins, Chairman, Geotechnical Committee, Manalta Coal Limited
L. Pitts, Chairman, Hydrogeological Committee, Monenco Consultants Ltd.
T. Sneddon, Alberta Office of Coal Research & Technology
B. Das, CANMET: Energy, Mines & Resources, Canada

2. Geotechnical Committee

This committee is responsible for the scope of the geotechnical component of the study, technical procedures, and for making recommendations to the Management Committee with regard to selection of competent geophysical and geological professionals to conduct the research.

The following representatives comprise the Geotechnical Committee:

G. Jenkins, Manalta Coal Ltd., (Chairman)
B. Das, CANMET: Energy, Mines & Resources, Canada
F. Khan, Terracon Geotechnique Ltd.
N. Wade, Monenco Consultants Limited

3. Hydrogeological Committee

Similarly, the Hydrogeological Committee is responsible for the scope and procedures within the hydrogeological component of the study.

The committee is comprised of the following representatives:

L. Pitts, Monenco Consultants Ltd. (Chairman)
N. Worsley, Saskatchewan Power Corporation
T. Dabrowski, Piteau Associates Engineering Ltd.
L. Nichols, Terracon Geotechnique Ltd.
G. Lobb, Syncrude Canada Ltd.
J. Pawlowicz, Alberta Research Council

4. Project Manager

The administration of the project and coordination of subcontractors is carried out by the Coal Mining Research Company acting as project manager, under the direction of the Management Committee. Additional responsibilities include technical and financial progress reports to the Management Committee, as well as preparation of project reports.

5. Expert Review Panel

The expert review panel has been selected to review the results of the research conducted during the project and to advise on the content and procedures required in subsequent phases. Panel members include:

S. Keys	United States Geological Survey, Denver, Colorado. (Retired)
P. Killeen	Geological Survey of Canada
J. Mwenifumbo	Geological Survey of Canada
C. Brawner	University of British Columbia
N. Morgenstern	University of Alberta
R. Bishop	BPB Instruments, (Canada) Ltd.

APPENDIX II

BPB GEOPHYSICAL TOOLS

SLIMLINE LOGGING BPB SERVICE MANUAL	SONDE MEASUREMENTS — SUMMARY (of subsurface leaflets 1 to 14)	FIELD INSTRUMENTATION SUBSURFACE No. A

Key·
- ● STANDARD
- ■ STANDARD with ALTERNATIVE OPTION
- ☐ ALTERNATIVE TO ■
- 1 Single arm caliper
- 2 Three arm caliper

SONDE		DIMENSIONS		MEASUREMENT (S)																		
MNEMONIC CODE	LEAFLET No.	MAXIMUM DIAMETER mm (ins)	LENGTH m (ft)	GAMMA RAY	CALIPER	LONG SPACED DENSITY (>30 cm)	INTERMEDIATE SPACED DENSITY (20–30 cm)	SHORT SPACED DENSITY (<20 cm)	COMPENSATED DENSITY	LONG SPACED NEUTRON (>30 cm)	SHORT SPACED NEUTRON (<30 cm)	COMPENSATED NEUTRON	SONIC (20, 20, 40 & 60 cm spacings)	RESISTANCE (Single Point)	SPONTANEOUS POTENTIAL	RESISTIVITY	MICRO RESISTIVITY	TEMPERATURE (ABSOLUTE, DIFFERENTIAL, DIFFERENCE)	HOLE DEVIATION (TILT AND AZIMUTH)	FORMATION DIP (DIP AND AZIMUTH)	SEISMIC REFERENCE SURVEY	VERTICAL SEISMIC PROFILING
DD1	1	48 (1⅞)	3.50 (11.5)	●	1●	●		●	●													
MS1	2	51 (2)	3.38 (11.1)										●									
SR1	3	60 (2⅜)	2.39 (7.8)																		●	●
RO1	4	38 (1½)	2.76 (9.0)													●						
DR1	5	48 (1⅞)	3.50 (11.5)	●	1●			●						☐			■					
DD2	6	38 (1½)	2.45 (8.0)	●		●	☐	■														
NO1	7	38 (1½)	2.41 (8.0) or 2.13 (7.0)							■	☐											
VO1/2	8	42 (1¹¹⁄₁₆)	2.63 (8.6)																●			
DV1 DV2	9	51 (2) 64 (2½)	4.50 (14.8) 5.30 (17.4)		2●														●	●		
TT1	10	38 (1½)	1.45 (4.8)															●				
CO1	11	38 (1½)	1.90 (6.3)		2●																	
RS1	12	33 (1⁵⁄₁₆)	1.48 (4.8)											●	●							
NN1	13	38 (1½)	2.47 (8.1)	●						●	●	●										
DD3	14	48 (1⅞)	3.50 (11.5)	●	●	●		●	●													

ADDITIONAL NOTES:

BPB's major slimline sondes and measurements, as summarised on the previous page, are described in some detail in the following 'subsurface' leaflets. This equipment offers a broad range of options to allow the selection of logging suites tailored to suit both application and hole condition. Such equipment is readily available out of most BPB operating centres.

These measurements may, however, be augmented by additional equipment offered on a more limited basis. Although not exhaustive, the following list will provide an indication of a few of these additional services. Some mobilisation notice is usually required.

— Casing Collar Locator (CCL)	— available in combination with a BPB single function Gamma Ray sonde.
— Sidewall Sonic	— for stationary measurements of 'S' wave velocities.
— Cement Bond Log (CBL)	— with either simple Amplitude or Variable Density (VDL) output.
— Spectral Gamma	— a basic four channel device for Ur, K, Th + Total Count, based on a BPB single function Gamma Ray sonde.
— Flowmeter	— available to suit a variety of hole diameters.
— Magnetic Susceptibility	—
— General Specifications	— the nominal Temperature and pressure specifications, as stated in the sonde leaflets, can often be uprated to meet specific borehole conditions or client requirements.

BPB welcome enquiries relating to the possible provision of any further slimline logging equipment and services not listed or specified herein.

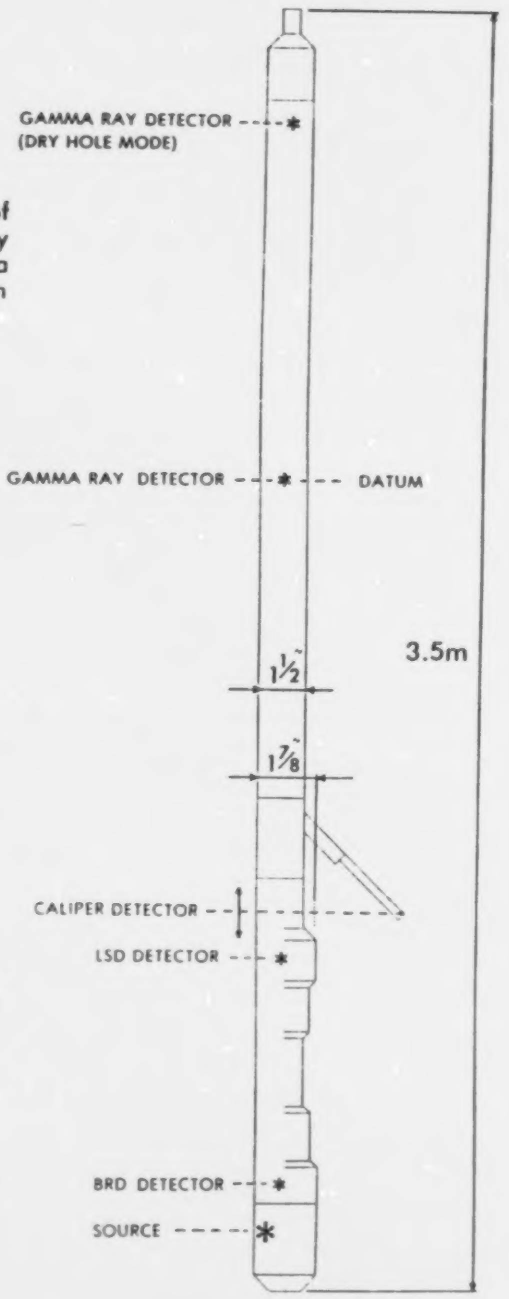
DD1 DUAL DENSITY, GAMMA RAY, CALIPER, SONDE.

(OR COAL COMBINATION SONDE CCS)

MEASUREMENTS:

LONG SPACING DENSITY (LSD)
BED RESOLUTION DENSITY (BRD)
COMPENSATED DENSITY
GAMMA RAY
CALIPER

The DD1 Sonde has been designed for the full range of borehole diameters, depths and conditions generally associated with slimhole drilling. All logs are recorded in a single run, with a selection of processing and presentation options available to suit specific requirements.



DD1 SCHEMATIC

GENERAL SPECIFICATIONS:

Length — 3.5 m (11.5')
Weight — 20 kg (44 lbs)
Diameter — 4.8 cm (1⅞") max
Temperature — up to 70°C (158°F)
Pressure — up to 210 kg/cm² (3000 p.s.i.)

OPERATING CONDITIONS:

Hole Depth — to a max of approx. 2000m (6500')
Hole Diameter — open hole: 6.5 to 30 cm (2.5" to 12")
casing or rods: 5.5 to 30 cm (2.0" to 12")

Logging Speed — standard logging: 9m/min (30'/min)
— detail logging: 2.25m/min (7.5'/min)
Logging Mode — Sidewall, Caliper eccentralised

Optimum calibration requires open, fluid filled holes with diameters less than 20 cm (8"). Results of a more qualitative nature will be obtained through casing or drill rods and/or without fluid. Significant caving of the borehole wall will adversely affect results.

TECHNICAL INFORMATION:

GAMMA RAY — Measurement of naturally occurring radioactivity utilizes an uncollimated Sodium Iodide Crystal coupled to a Photo Multiplier Tube based amplifying system. Calibration, by active field jig allows linear presentation in API units with borehole correction. Some sondes offer a remote detector position option, to prevent interference from the source in dry holes.

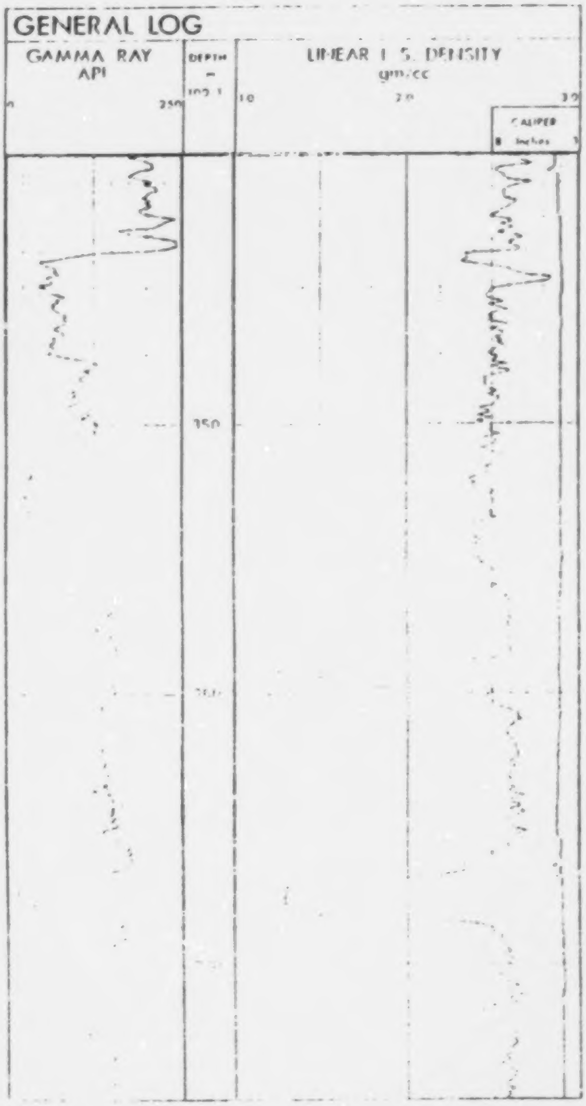


Fig. 1 — LINEAR DENSITY GENERAL SCALE.

DENSITY — Measurement of scattered radiation levels is made with two independent detecting systems, both similar to the Gamma Ray detector but incorporating crystal shielding (sidewall collimation) and cable deadtime correcting circuitry. Calibration utilizes large passive base facilities and active field jigs to allow log presentation in gm/cc.

LSD — The deeper reading device, with a source to detector spacing of 48 cm (19"), provides the definitive density log in most borehole conditions and is presented:

— with linear response, facilitating full 1-3 gm/cc range evaluation,

and/or — with logarithmic response, enhancing the 1-2 gm/cc range.

Borehole corrections are applied and compensation is available, incorporating the BRD, to improve density measurement in difficult hole conditions.

BRD — With a spacing 15 cm (6") this shallower reading measurement produces an essentially linear response density log as both:

— an independent high resolution log for precise boundary definition.
Digital and Deconvolution Filter options can, under ideal conditions, provide resolution enhancement down to 5 cm (2").

— on LSD compensation factor.

CALIPER — A single arm electro mechanical device is held closed for entry into the borehole and activated during the logging run. Field calibration produces a precise linear measurement of hole diameter and caving profile. Hole diameter ranges:

Standard arm	4.8 to 20 cm (1⅞" to 8")
Long arm	4.8 to 30 cm (1⅞" to 12")

SOURCE — A doubly encapsulated sealed source of Caesium 137 at an activity of 100 mCi. is mounted within a sidewall collimated holder and locked securely to the sonde during logging operations. This source holder is transported in a purpose designed shield with a surface radiation level less than 10 mrem/hr.

PRESENTATION:

Logs are recorded in Metric or Imperial units and presented on a standard 6 track API logging chart with full flexibility of scales and format. 'General' vertical scales range upwards from 100:1 whilst 'Detail' scale options, reserved for closer investigation of zones of interest, range down to 10:1. Some of the more usual presentations include:

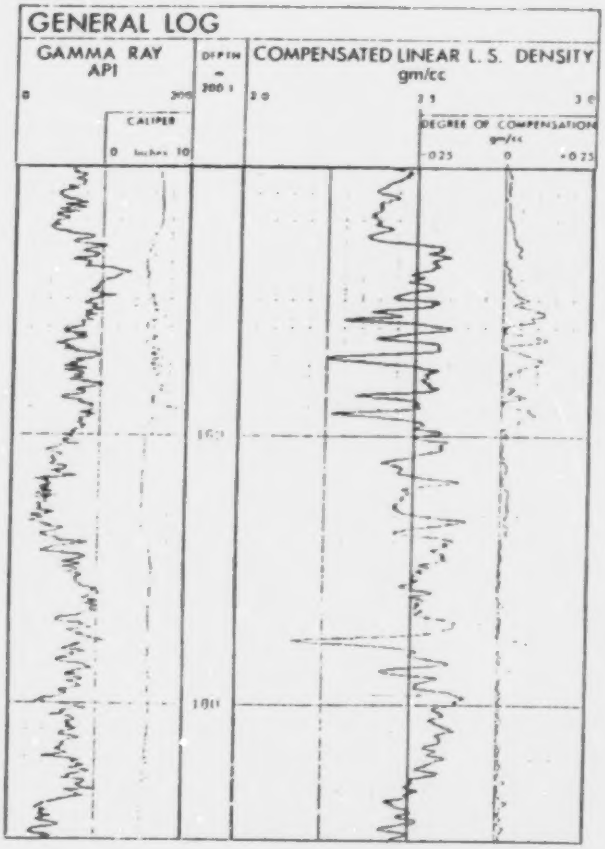


Fig. 2 — COMPENSATED DENSITY GENERAL SCALE.

LINEAR DENSITY — *GENERAL SCALE (fig. 1)*

Linear LS Density over a range of either 1-3 gm/cc or 2-3 gm/cc depending on density range encountered.

Linear Gamma Ray and Caliper on suitable scales.

LOGARITHMIC DENSITY — *GENERAL SCALE*

As fig. 1 except that the LS Density is presented with logarithmic response to provide enhancement over the 1-2 gm/cc range.

COMPENSATED DENSITY — *GENERAL SCALE (fig. 2)*

Similar to fig. 1 except that the LS Density is compensated by the BR Density and the 'degree of compensation' included.

DETAIL DENSITY — *DETAIL SCALES (fig. 3a, b, c)*

A comparison of the three density options: LSD Linear, LSD Logarithmic and BRD (Linear), on detail scales; an illustration of scale flexibility and tool performance through seams or zones of interest over the full 1-3 gm/cc range.

Density correction and processing options vary according to the computational power of the surface equipment and may be summarized as follows:

Corrected/Processed for the effects of:	Surface Equipment		
	Standard Unit	Log Processor Unit	Computer Graphics Unit
Borehole diameter	Yes	Yes	Yes
Fixed 1.0 gm/cc mud weight	Yes	—	—
Mud weight as input	—	Yes	Yes
Formation Z/A effect	Yes	Yes	Yes
Detector deadtime	Yes	Yes	Yes
Cable deadtime	Yes	Yes	Yes
LSD Linearization option	No	Yes	Yes
LSD Compensation (with BRD) option	No	Yes	Yes
BRD Deconvolution option	No	Yes	Yes
Gamma Ray Stripping	No	No	Yes
Variable Caliper measuring point	No	No	Yes

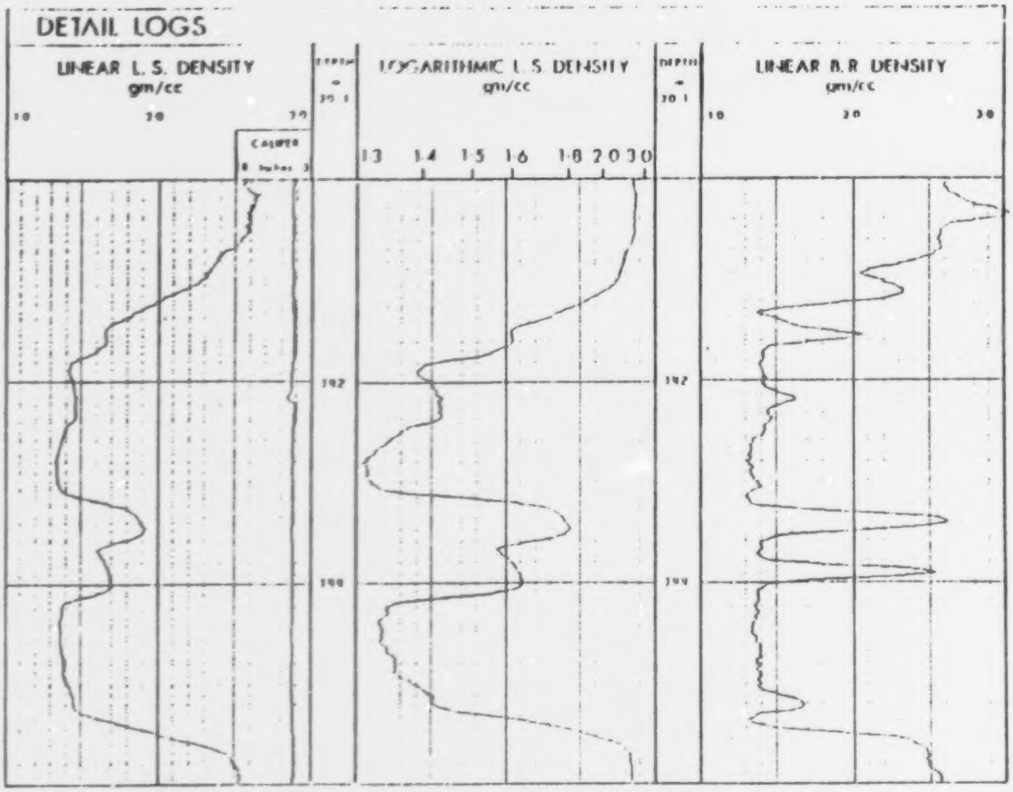


Fig. 3 — DETAIL SCALE DENSITY PRESENTATION OPTIONS.

APPLICATION SUMMARY:

GAMMA RAY — Shale Content, Lithology Identification and Correlation.

DENSITY : LSD — Porosity, Lithology Identification and Correlation plus quantitative evaluation of: Lithology, Formation Properties, and Strength Index (with MC Sonic Sonde).

: BRD — Precise boundary definition usually to ±2 cm (plus LSD compensation).

CALIPER — Borehole diameter and caving profile (plus sidewall configuration and density correction).

The DD1 suite is seen as a basic slimhole evaluation package, providing both general lithology and detailed seam information in one logging run. Additional sonde runs are available to complement the DD1 service according to specific interpretation requirements.

REFERENCES:

Further information on many aspects of the DD1 service may be found in the following BPB publications, available on request.

1. BPB Coal Interpretation Manual
2. The Radiation Density Log Applied to the Resolution of Thin Beds in Coal Measures — J.R. Samworth
3. Slimline Dual Detector Density Logging, a Semi-Theoretical but Practical Approach to Correction and Compensation — J R. Samworth

MS1 MULTICHANNEL SONIC SONDE.
(OR MCS)

MEASUREMENTS:

ACOUSTIC VELOCITY LOGS AT:

20cm (8") RESOLUTION, DESPIKED
40cm (16") RESOLUTION, DESPIKED
60cm (24") RESOLUTION, DESPIKED
20cm (8") RESOLUTION, UNPROCESSED

PLUS INTEGRATED SONIC LOG

The MS1 Sonde provides high quality Sonic Transit Velocity data, within a slim diameter and at a variety of vertical resolutions, throughout a comprehensive range of borehole diameters and conditions.

GENERAL SPECIFICATIONS:

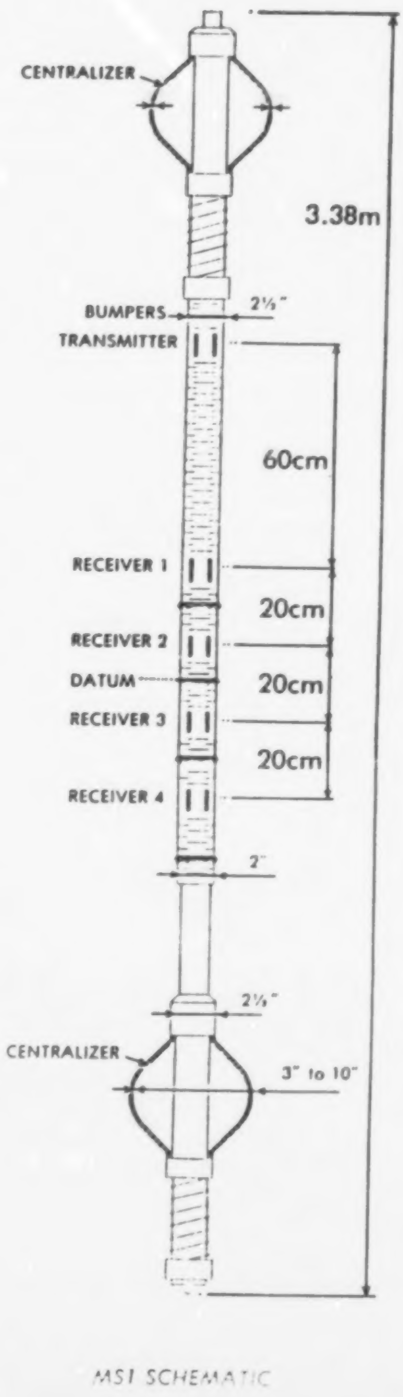
Length — 3.38m (11.1')
Weight — 16kg (35 lbs) without centralizers
22kg (49 lbs) with centralizers
Diameters — basic sonde 51m (2")
— with bumpers/centralizers 65m (2.5")
Temperature — up to 70°C (158°F)
Pressure — up to 210 kg/cm² (3000 psi)

OPERATING CONDITIONS:

Hole Depth — to a max. of approx. 2000m (6500')
Hole Diameter — 65mm (2.5") to 90m (3.5") without centralizers
— 90mm (3.5") to 300+mm (12+") with centralizers
Logging Speed — Standardly: 9m/min (30'/min)
Logging Mode — Centralized, where borehole diameter and conditions permit, with a full 360° window for all 5 transducers (one transmitter and four receivers).

Precise in-built electronic calibration ensures the accuracy of all transit timings, allowing downhole processing of velocity data, prior to surface transmission. Sonic logging will be successful only in Open (Uncased), Fluid Filled boreholes.

Sonic measurements will become problematic in badly caved sections of the borehole or in unconsolidated (or other) formations where adequate acoustic coupling cannot be achieved.



MS1 SCHEMATIC

TECHNICAL INFORMATION:

A ceramic transmitter T is fired with a high voltage pulse every 0.1 sec. causing acoustic energy to enter the formation, via the borehole fluid (essential for efficient coupling), as a compression wave. Fig. 1.

Receivers R1, R2, R3, R4 are successively stimulated by this same compression wave after passing through sections of the formation between the transmitter and appropriate receiver. The distance between each of the receivers is fixed, and of course known precisely. Consequently measurement of the time taken for the wave to pass between receiver pairs will enable the calculation of its velocity, normally known as the Sonic Velocity.

By incorporating pre-programmed microprocessors in the sonde various combinations of receiver pairs can be selected and processed simultaneously. The following options are standardly available:

R1-R2 20cm (8") —
HIGH RESOLUTION CHANNEL No.1
R2-R4 40cm (16") —
MEDIUM SPACING CHANNEL No. 2
R1-R4 60cm (24") —
LONG SPACING CHANNEL No. 3
R3-R4 20cm (8") —
DISCONTINUITY CHANNEL No. 4

The MS1 Sonde calculates each of these four velocities every 0.1 sec. (equivalent to 1.5cm at the standard 9m/min. logging speed), transmitting results for surface recording as continuous depth based logs.

Discontinuities in the formation can often cause interruption to the compression wave, causing unwanted spikes on the log. In Channels 1, 2 and 3, these effects have been identified and removed, again by the use of downhole microprocessors. Channel 4 is presented in its original unprocessed form, providing both a quality control on the processed channels and also a means of identifying zones of high discontinuity, eg fracture detection.

System design ensures that the first arrival of the compression wave at all receivers results, in normal conditions, from transit paths through the formation rather than through the body of the sonde or through the borehole fluid. Limiting extremes of borehole diameter and formation velocity combinations, beyond which 'first arrival' problems will be encountered, are listed in the Application section.

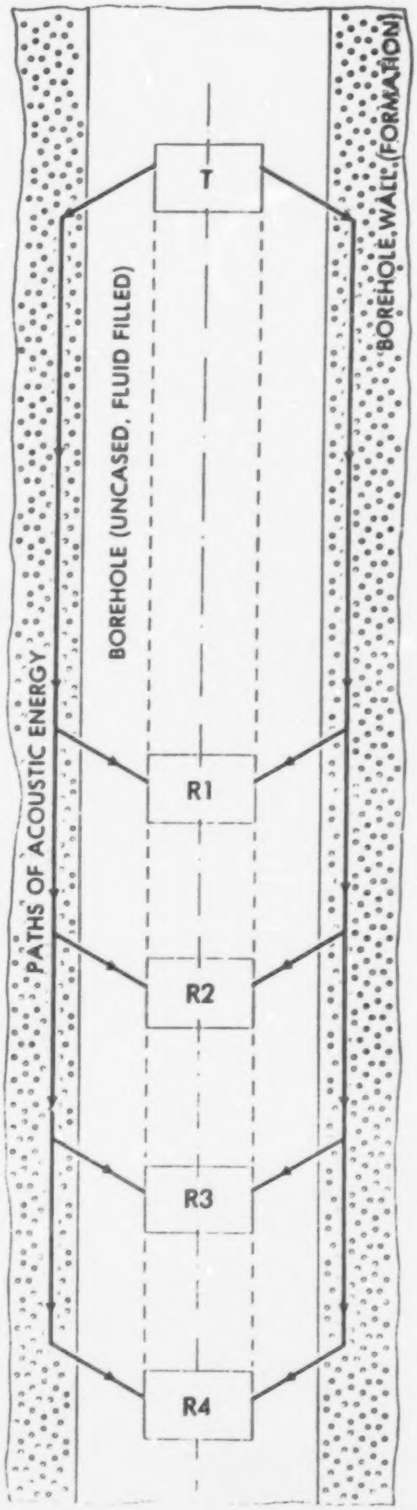


Fig 1 — TRANSDUCER SCHEMATIC

PRESENTATION:

A full flexibility of vertical scales (either metric or imperial) and presentation formats is available, to include up to all four Velocity Channels and Integrated data.

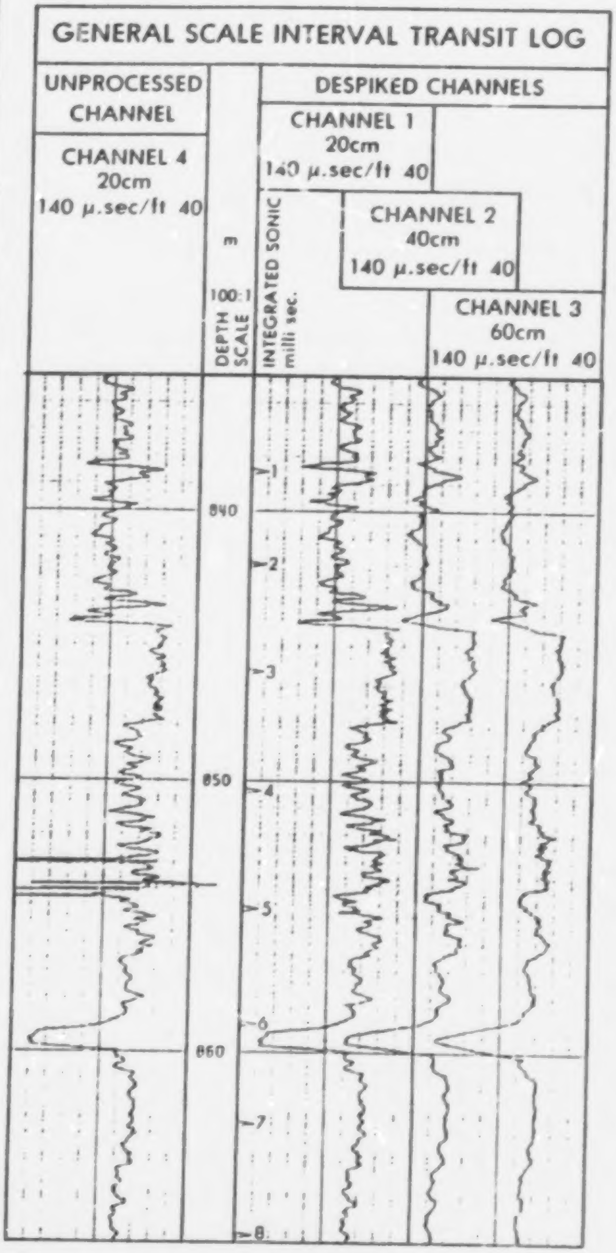


Fig. 2 — PRESENTATION EXAMPLE

Fig. 2 is a comprehensive illustration of all Velocity logs, together with a Channel 2 based Integrated Sonic log, at a 100:1 metric scale.

The 'spiking' effects of discontinuity or other features can be readily seen in this example. Channel 4, within the 853-855m interval, contains spiking features which have been automatically identified as geophysically invalid and processed out of the remaining channels.

Notes:
- Velocity logs are usually presented in either μ.sec/ft or μ.sec/m.
- The Integrated Sonic Log, based on any of the Velocity Channels, is available as a surface processing option.
- A Channel 1 deconvolution option is available as a surface processing procedure to further enhance the resolution of this high resolution channel, from 20cm to 14cm.

APPLICATION SUMMARY:

LONG SPACING (60cm) CHANNEL No. 3 — provides the best average formation velocity and minimises the effects of any cavings. This channel is ideal for porosity determination, lithology determination, correlation, forming an integrated sonic log for seismic correlations and for combining with a density log for rock strength determinations.

HIGH RESOLUTION (20cm) CHANNEL No. 1 — is suitable for deliniation of bed boundaries and structures within the seams. The high resolution allows more detailed analyses of rock strength and seam quality. Deconvolution options offer further resolution enhancement.

MEDIUM SPACING (40cm) CHANNEL No. 2 — is required when borehole conditions, mainly because of caving, preclude the use of the HR Channel. This spacing is often preferred in narrow diameter boreholes to the LS Channel as more detail is displayed.

DISCONTINUITY (20cm) CHANNEL No. 4 — monitors the original unprocessed signal and is thus useful for indications of fractures and other conditions likely to produce spiking effects.

INTEGRATED SONIC — Usually derived from either the LS or HR Channel, depending on hole condition, and used as an aid for seismic interpretation.

N.B. All four channels are valid for rock velocities down to 150μ.sec/ft in holes up to 10" diameter. Additionally for the same range of rock velocities channel 2 is valid up to 13" diameter and channel 4 up to 16".

REFERENCES:

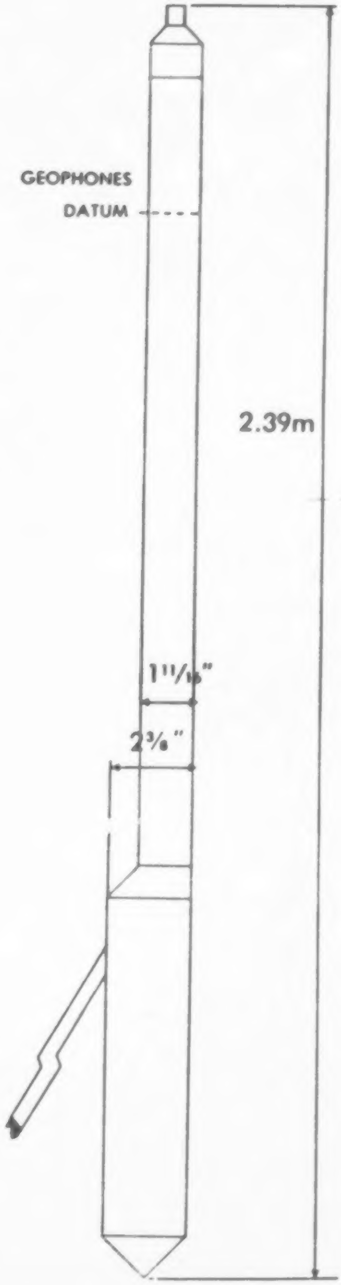
Further information on the MS1 Service may be found in the:
— BPB Coal Interpretation Manual,
a BPB publication available on request.

SR1 SEISMIC REFERENCE SONDE.

MEASUREMENTS:

MEAN TIMES mSec
CORRECTED 2-WAY TIMES mSec
AVERAGE VELOCITY m/sec TO SPECIFIC HORIZONS
INTERVAL VELOCITY m/sec BETWEEN HORIZONS
RMS VELOCITY m/sec

The SR1 Sonde and SRS Survey Panel can be set up with a winch unit as a stand alone service. In this case the normal BPB Slimline Logging Unit is not required on site.



GENERAL SPECIFICATIONS:

Length — 2.39m (7.8′)
Weight — 20Kg (45lbs)
Diameter — 6cm (2⅜")
Temperature — up to 70°C (158°F)
Pressure — 492Kg/cm² (7,000psi)

OPERATING CONDITIONS:

Hole Depth — to max. of approx. 3,050m (10,000′)
Hole Diameter — 7.5cms to 33.0cms (3" to 13")

Optimum results require open fluid filled holes but good results can usually be obtained in dry or cased holes.

The BPB airgun requires a fluid filled pit 2mx2mx2m (6′x6′x6′) for efficient acoustic coupling. The airgun may be replaced by the client's own wave propagating device or explosives.

TECHNICAL INFORMATION:

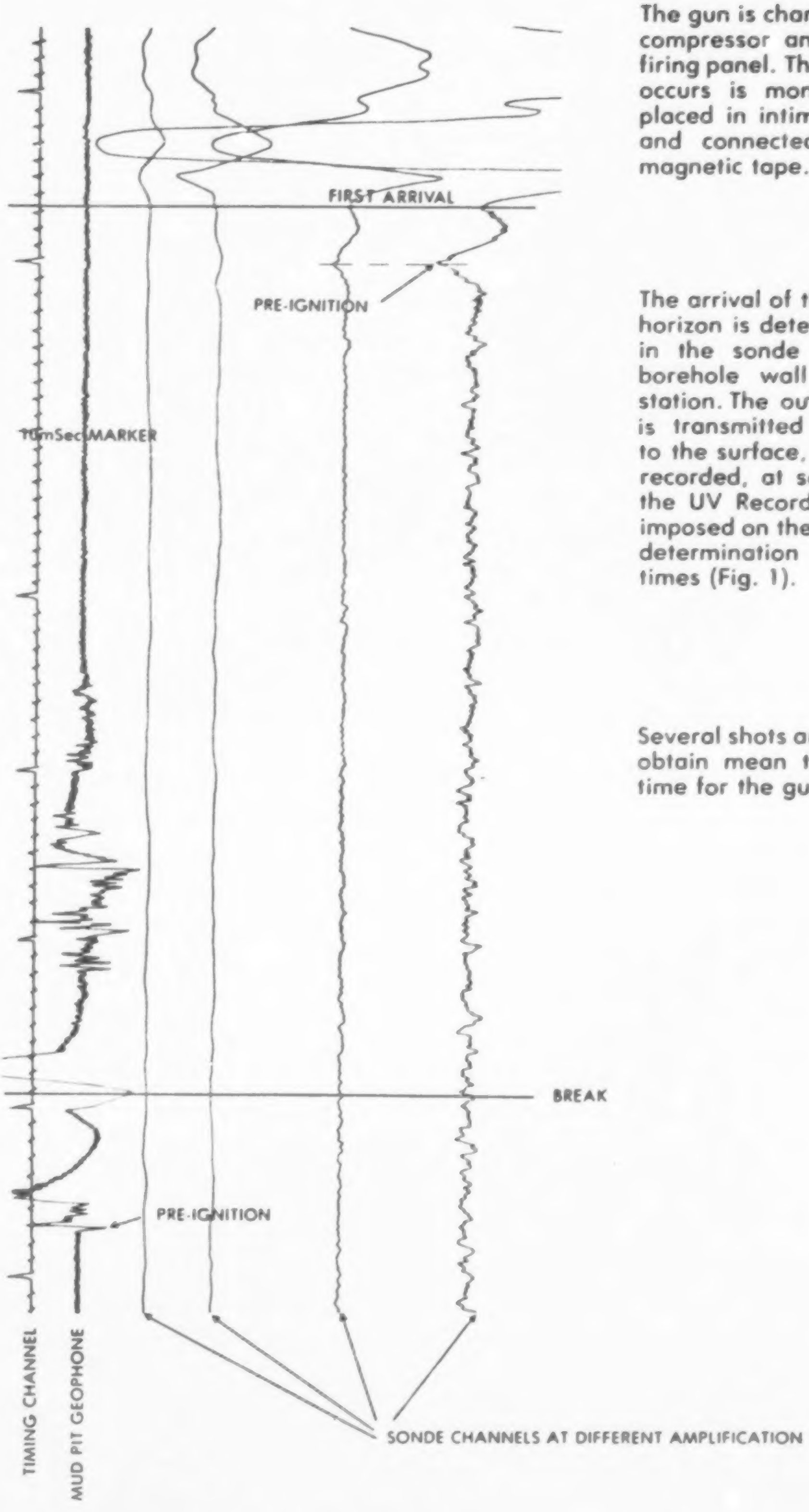


Fig. 1 UV RECORDER OUTPUT

The gun is charged by a high pressure air compressor and triggered by a remote firing panel. The time at which detonation occurs is monitored by a hydrophone placed in intimate contact with the gun and connected to a UV recorder or magnetic tape.

The arrival of the compression wave at a horizon is detected by a geophone array in the sonde which is locked to the borehole wall at the required depth station. The output signal from the sonde is transmitted via the logging cable to the surface, where the wave train is recorded, at several different gains, on the UV Recorder. Timing lines are also imposed on the output to ensure accurate determination of the required travel times (Fig. 1).

Several shots are taken at each horizon to obtain mean times. A typical recharge time for the gun being 1 minute.

CORRECTIONS:

The recorded seismic times are corrected using the following time correction factor te, to allow for the different depths of the weathering, the gun depth, the elevation of ground level above the seismic datum, the gun and hydrophones separation together with the various velocities involved near surface is given by:

$$te = \frac{h}{Vw} - \frac{(dw - dg)}{Vwe} - \frac{(EGL - dw)}{Ve}$$

Where		
	h	is the separation of gun and hydrophone
	Vw	is the mud pit fluid velocity
	dw	is the weathering depth below ground level
	dg	is the gun depth below ground level
	EGL	is the elevation of the SRS datum above the seismic datum
	Vwe	is the weathering velocity
	Ve	is the elevation velocity

Ve, the elevation velocity, is:

= Vwe if EGL < dw

= velocity of first layer below dw if EGL > dw.

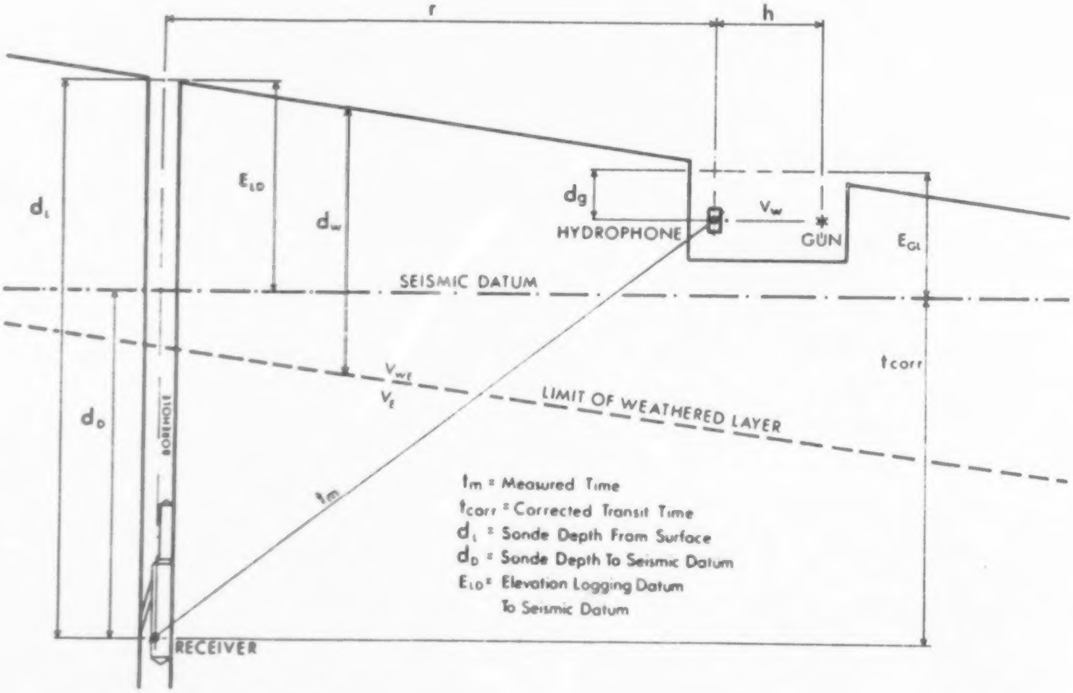

r
h
d_L
E_{LD}
d_w
d_g
V_w
HYDROPHONE
GUN
E_{GL}
SEISMIC DATUM
t_{corr}
V_{we}
V_e
LIMIT OF WEATHERED LAYER
d_D
BOREHOLE
tm
t_m = Measured Time
t_{corr} = Corrected Transit Time
d_L = Sonde Depth From Surface
d_D = Sonde Depth To Seismic Datum
E_{LD} = Elevation Logging Datum To Seismic Datum
RECEIVER

Fig. 2 SEISMIC REFERENCE SURVEY SCHEMATIC

PRESENTATION:

Logged Depth m	Measured Times m sec	Mean Times m sec	Depth below Seismic Datum m	Corrected 2 Way Times m sec	Average Velocity m sec	Interval Velocity m sec	R M S Velocity m sec
32 20	25 25	25	32 20	34 6	1860 7	1860 7	1860 7
466 00	187 187	187	466 00	378 3	2463 4	2524 1	2470 9
488 69	191 191	191	488 69	386 5	2529 1	5589 9	2575 5
718 45	239 239	239	718 45	483 1	2974 3	4754 4	3135 0
801 00	265 265	265	801 00	535 2	2993 3	3169 1	3138 4
842 00	278 278	278	842 00	561 2	3000 5	3148 9	3138 9
875 39	286 286	286	875 39	577 3	3032 8	4164 2	3171 8
925 00	302 302	302	925 00	609 3	3036 2	3096 8	3167 9
989 00	318 318	318	989 00	641 4	3084 0	3993 3	3214 2
1060 00	336 337	336 5	1060 00	678 4	3124 9	3832 7	3251 0
1106 9	352 352	352	1106 96	709 4	3120 6	3027 4	3241 6

Fig. 3 TABULATED DEPTHS AND VELOCITIES

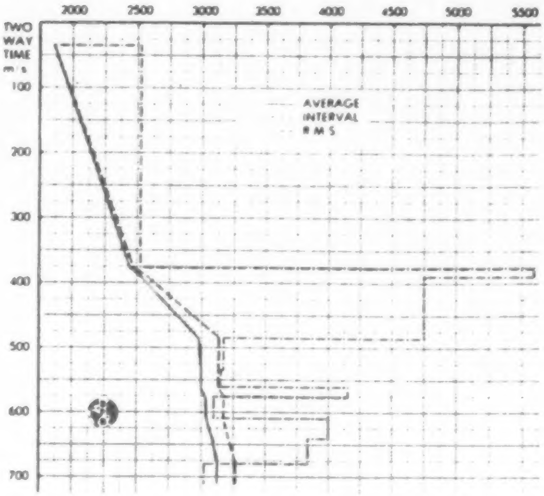


Fig. 4 PLOT OF AVERAGE INTERVAL AND RMS VELOCITIES Vs TWO WAY TIME

Interpolated Depths m	2 Way Times m sec	Interpolated 2 Way Times m sec	Depths m
50	48 8	50	51 6
100	88 6	100	114 7
150	127 9	150	177 8
200	167 6	200	240 9
250	207 2	250	304 0
300	246 8	300	367 1
350	286 4	350	430 2
400	326 0	400	520 9
450	365 7	450	639 8
500	391 2	500	745 2
550	412 2	550	824 3
600	433 3	600	910 6
650	454 3	650	1005 5
700	475 3	700	1092 7
750	500 0		
800	534 6		
850	565 1		
900	593 2		
950	621 8		
1000	647 1		
1050	673 2		
1100	704 8		

Fig. 5 TABULATED INTERPOLATED DEPTHS AND TWO WAY TIMES

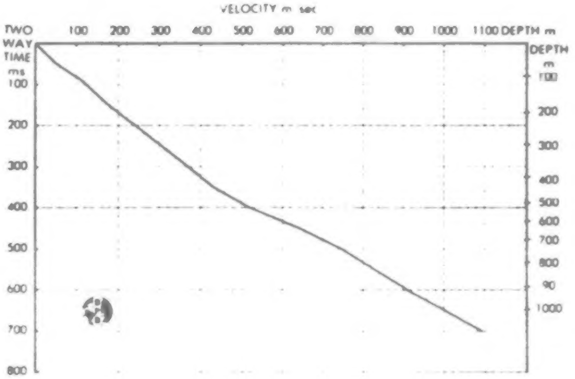


Fig. 6 PLOT OF TWO WAY TIME Vs DEPTH

APPLICATIONS:

Accurate conversion from depth to seismic time and vice versa. The data can also be used to correct sonic logs, whether for more accurate log interpretation or to enable the depth to time conversion to be performed continuously throughout a borehole. This conversion enables a synthetic seismogram to be produced.

RO1 FOCUSSED ELECTRIC SONDE

(OR FE MK II SONDE)

MEASUREMENTS:

FORMATION RESISTIVITY

The RO1 Sonde is a single function 3 electrode laterolog device combining high power of vertical resolution and intermediate depths of investigation. The result is a quantitative measure of formation resistivity well suited to the interpretation of formation properties in slim holes.

GENERAL SPECIFICATIONS:

Length — 2.76m (6.5') Sonde
— 12.3m (40.4') Sonde + Bridle (Standard)
— 7.3m (24') Sonde + Bridle (Shallow hole)
Weight — 15kg (33lbs)
Diameter — 3.8cm (1½")
Temperature — up to 70°C (158°F)
Pressure — up to 210kg/cm^2 (3000psi)

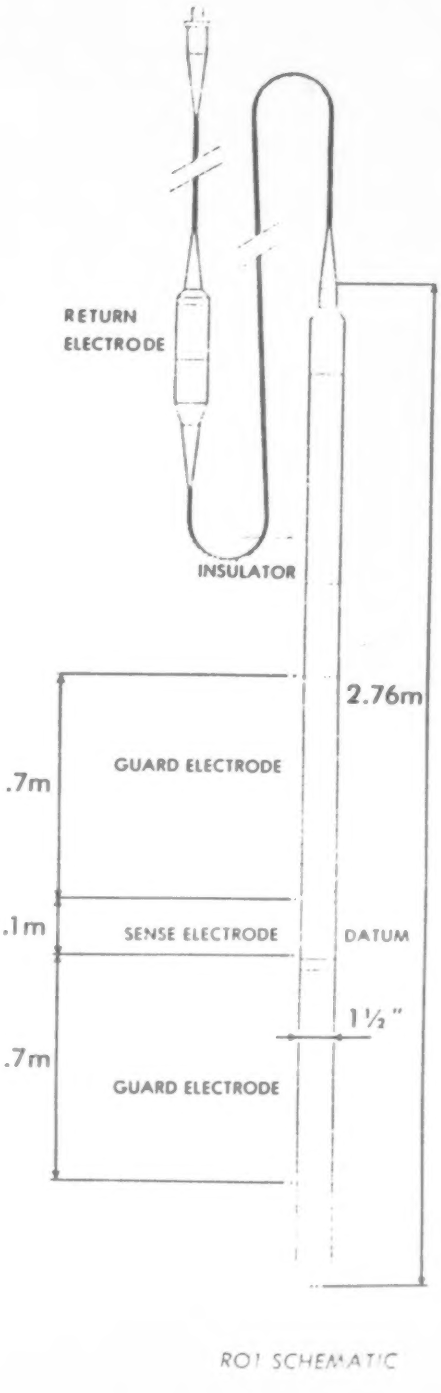
OPERATING CONDITIONS:

Hole Depth — to a max. of approx. 2000m (6500')
Hole Diameter — open hole 5.0cm to 25+cm (2.0" to 10+")

Logging Speed — standardly 9m/min (30'/min)
Logging Mode — free running
Resistivity range — 0.2 to 20,000 ohm m

Open, fluid filled holes are a prerequisite, and optimum hole diameters less than 20cm (8"). Fluid resistivities should be as low as possible, this requirement being more important in low resistivity formations.

Logging near the surface is limited by the requirement for the bridle to be in the fluid of the open hole. Excessive borehole casing will adversely affect results.



RO1 SCHEMATIC

TECHNICAL INFORMATION:

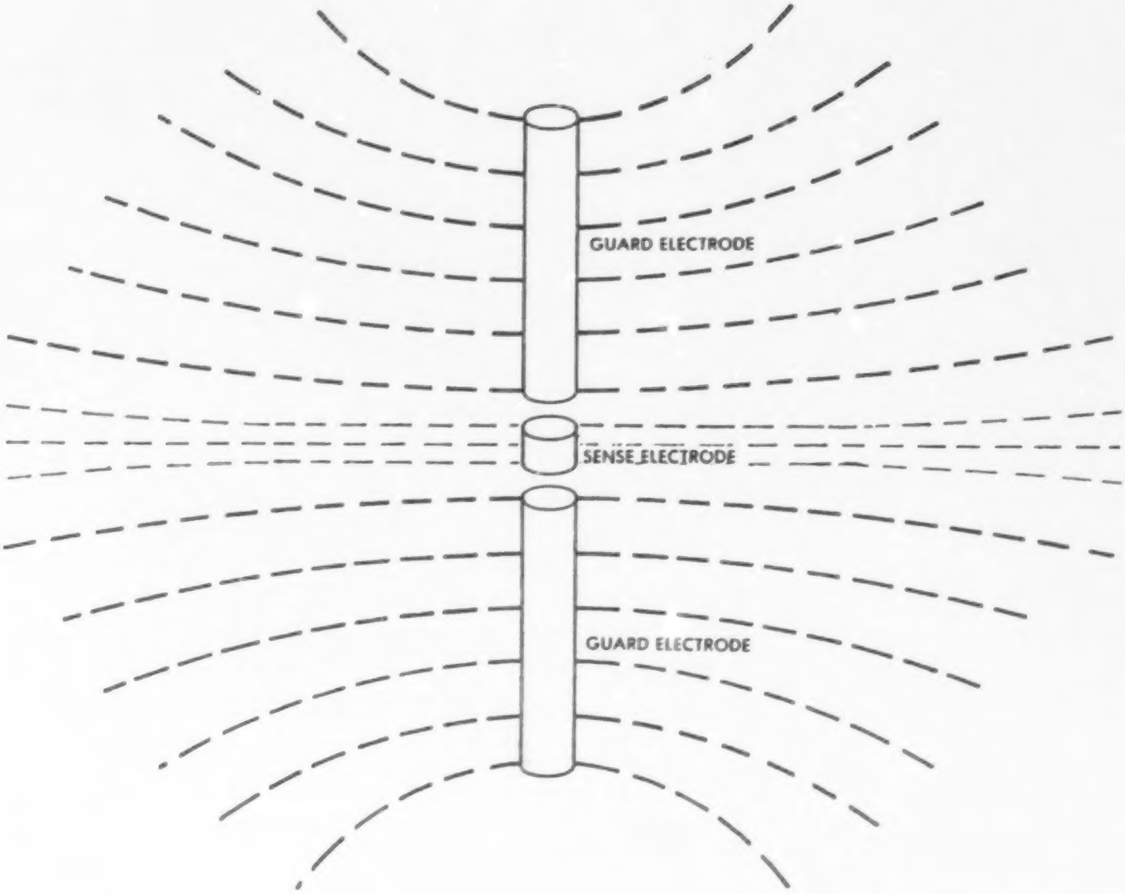


Fig. 1 CURRENT DIAGRAM

An electric current is established from the 'sense' electrode via the borehole fluid into the formation, the circuit being eventually completed through surface electronics and logging cable.

The initial focussing of this current (fig. 1) into a narrow 360° cylindrical disc is achieved with a secondary circuit set up from the two larger 'guard' electrodes, this circuit being completed through a further electrode positioned at an optimum distance above the sonde — although this distance can be decreased if near surface measurement is required.

Sonde electronics hold the potential differences between the sense and guard electrodes at zero hence the focussing effect, and monitor both the sense current and voltage levels throughout the full range of resistivities encountered.

Combination of these values yield, via Ohm's law, a measure of the resistance seen by the sense electrode. Translation of this resistance into a continuous depth based log of formation resistivity follows, with the application of conversion and correction based on sonde geometry, borehole diameter and mud resistivity — see reference 2.

PRESENTATION:

Logs may be recorded in Metric or Imperial depth scales and are available with a full flexibility of vertical and horizontal scales.

The Focussed Electric measurement is usually presented on a logarithmic scale over several decades, to meet the range of resistivities encountered.

Linear presentation is also available if specifically required.

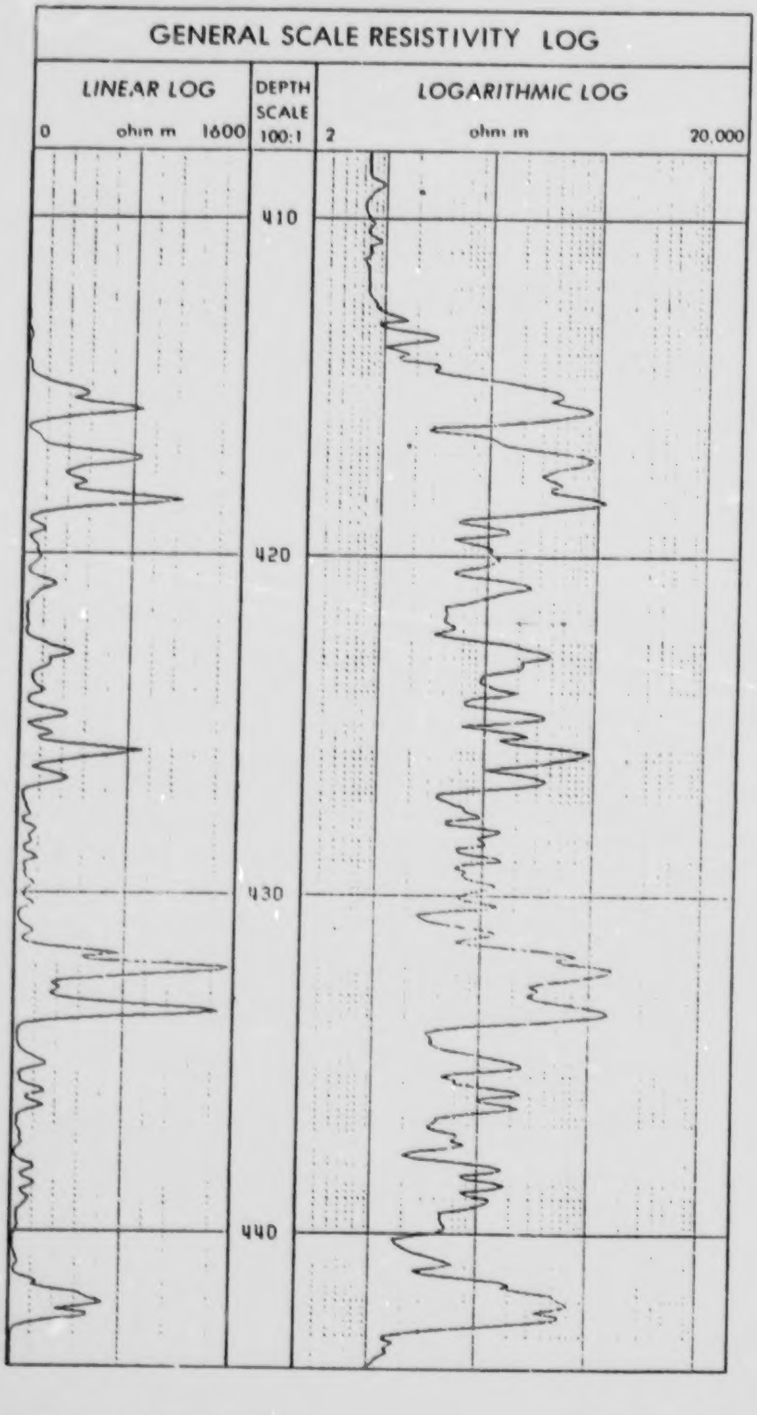


Fig. 2 LOG PRESENTATION

APPLICATIONS

The RO1 Sonde's Focussed Electric log of formation resistivity combines the advantages of a Single Point device's high resolution (but uncalibrated) with a Normal or Lateral device's calibration ability (although poor resolution) — whilst maintaining a depth of investigation realistic in terms of slimhole conditions.

The resulting log provides not only valuable lithology correlation data but also a quantitative measure of formation properties to enable further interpretation to be considered.

REFERENCES:

Further information on Focussed Electric measurement may be found in the following BPB publications, available on request:

1. BPB Coal Interpretation Manual.
2. A Focussed Resistivity Tool for Slimline Coal Logging Systems — J R Samworth and M A Cherrie.

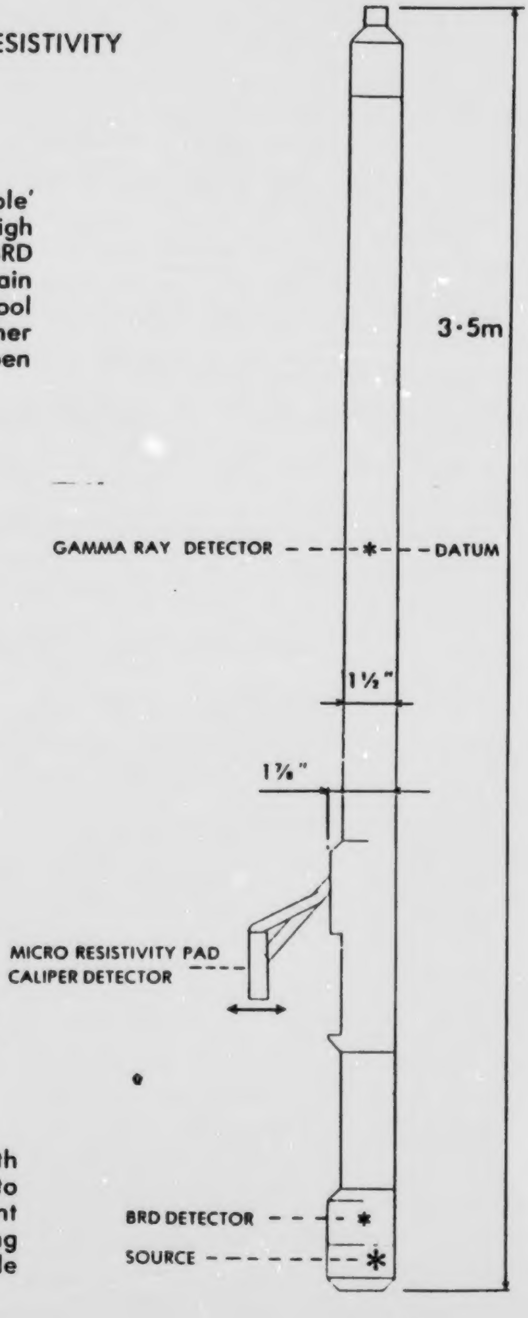
DR1 DENSITY, RESISTIVITY, GAMMA RAY, CALIPER, SONDE.

(or High Resolution Coal Sonde HRCS)

MEASUREMENTS:

BED RESOLUTION DENSITY (BRD)
MICRO FOCUSSED (OR SINGLE POINT) RESISTIVITY
GAMMA RAY
CALIPER

The DR1 Sonde has been designed as a 'good hole' alternative to the DD1, combining an extremely high resolution Micro Resistivity device with an upgraded BRD measurement. Gamma Ray and Caliper logs are again included to provide further correlation, evaluation and tool alignment functions. The resulting log suite offers a higher resolution approach to basic logging in better quality open hole environments.



GENERAL SPECIFICATIONS:

Length — 3.50m (11.5')
Weight — 25kg (55lbs)
Diameter — 4.8cm (1⅞") Max.
Temperature — up to 70°C (158°F)
Pressure — up to 210kg/cm² (3000 psi)

OPERATING CONDITIONS:

Hole Depth — to a max. of approx. 2000m (6500')
Hole Diameter — open hole 6.5 to 30cm (2.5" to 12")
Logging Speed — standard logging: 9m/min (30'/min)
— detail logging: 2.25m/min (7.5'/min)
Logging Mode — sidewall, caliper eccentralised

Optimum logging requires open, fluid filled holes, with diameters less than 15cm (6"), although a modification to the resistivity arm can often provide Single Point Resistance logs in 'dry' holes. The adverse effects of caving can be more pronounced with this high resolution sonde than with the DD1 and care should be exercised.

TECHNICAL INFORMATION:

Gamma Ray — Measurement of naturally occurring radioactivity utilizes an uncollimated Sodium Iodide Crystal coupled to a Photo-multiplier Tube based amplifying system. Calibration, by active field jig, allows linear presentation in API units.

BR Density — Measurement of the level of scattered radiation uses a detecting system similar to that of the Gamma Ray but incorporating crystal shielding (sidewall collimation) and deadtime correcting circuitry. A two point calibration system utilizes large passive base facilities, translating responses into the field through more portable facilities to allow log presentation in gm/cc. With a source to detector spacing of 15cm (6") the BRD combines high resolution with quantitative measurement of bulk density for detailed formation evaluation. Optional Digital and Deconvolution filter facilities can provide further resolution enhancement down to 7cm (3").

Micro Resistivity — A sidewall, caliper pad mounted device provides, through a miniature laterolog arrangement, a shallow investigation log of electrical resistance. Kept in close contact with the borehole wall this pad, with a ·5cm sense electrode, responds to formation resistivity changes with ultra high vertical resolution, enabling more precise boundary and parting definition to be achieved.

(A Single Point Scratcher device is available as an alternative means of obtaining an electric log and is often feasible in 'dry' boreholes).

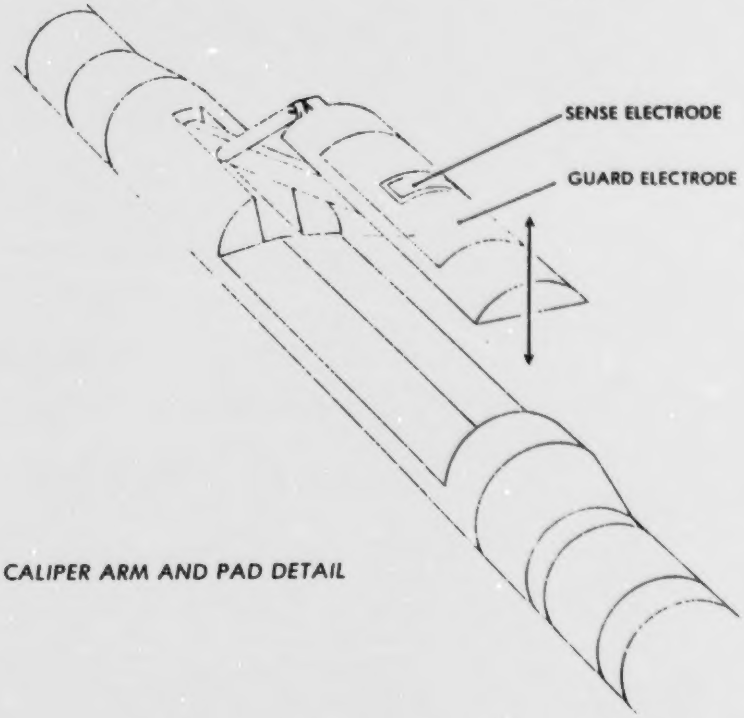


Fig. 1 — CALIPER ARM AND PAD DETAIL

Caliper — A single arm electro mechanical device carries the micro resistivity pad or single point electrode. It is held closed for entry into the borehole and activated during the logging run to provide caliper logging and to maintain sidewall configuration. Field calibration produces a linear measurement of hole diameter in inches or cm.

Hole diameter ranges:	Micro resistivity pad:	4.8cm to 30cm (1⅞" to 12")
	Scratcher arm:	4.8cm to 35cm (1⅞" to 13")

Source — A doubly encapsulated sealed source of Caesium 137 at an activity of 10 m Ci is mounted within a sidewall collimated holder and locked securely to the sonde during logging operations. This source holder is transported in a purpose designed shield with a surface radiation level less than 8 mrem/hr.

PRESENTATION:

Logs are recorded in Metric or Imperial units and presented with full flexibility of scales and format. 'General' vertical scales range upwards from 100:1 whilst 'Detail' scale options, reserved for closer investigation of zones of interest, range down to 10:1. Some of the more usual presentations include:

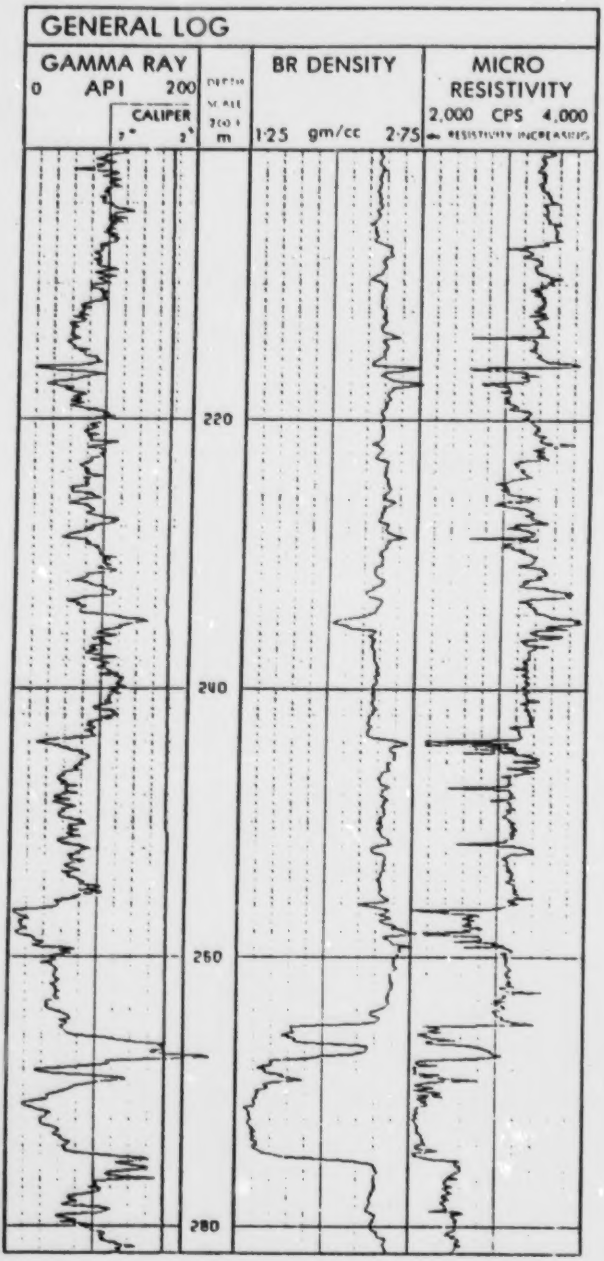
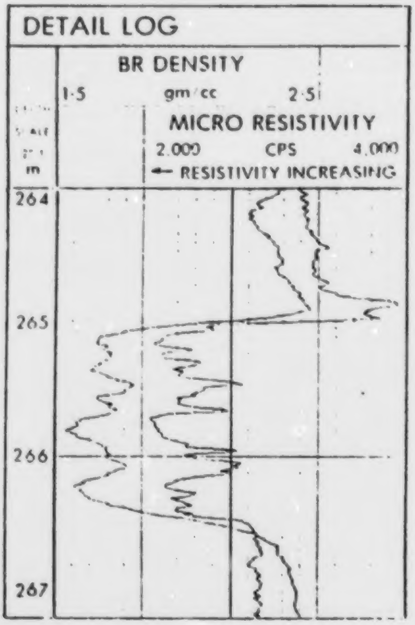


Fig. 2 — A GENERAL SCALE (200:1) PRESENTATION

Fig. 3

DETAIL SCALE LOGS (20:1), **recorded through a coal seam to illustrate more clearly the high powers of vertical resolution of both the BRD and, to an even greater extent, the Micro Resistivity.**



APPLICATION SUMMARY:

GAMMA RAY	— Shale Content, Lithology Identification and Correlation.
DENSITY: BRD	— Lithology Identification and Correlation plus quantitative evaluation of: Lithology, Porosity and other Formation properties and Strength Index (with Sonic) all at increased vertical resolution .
MICRO RESISTIVITY	— Precise Boundary definition and indication of in seam shale and dirt partings.
CALIPER	— Borehole diameter and caving profile (plus sidewall configuration and density correction).

The DR1 suite provides improved qualitative and quantitative evaluations in good quality narrow diameter boreholes. It should be seen as a 'good caliper' alternative to the more universally applicable DD1 which, because of its deeper reading LS Density channel, can better cope with caving conditions.

REFERENCES:

Further information on many aspects of the DR1 service may be found in the following BPB publications, available on request.

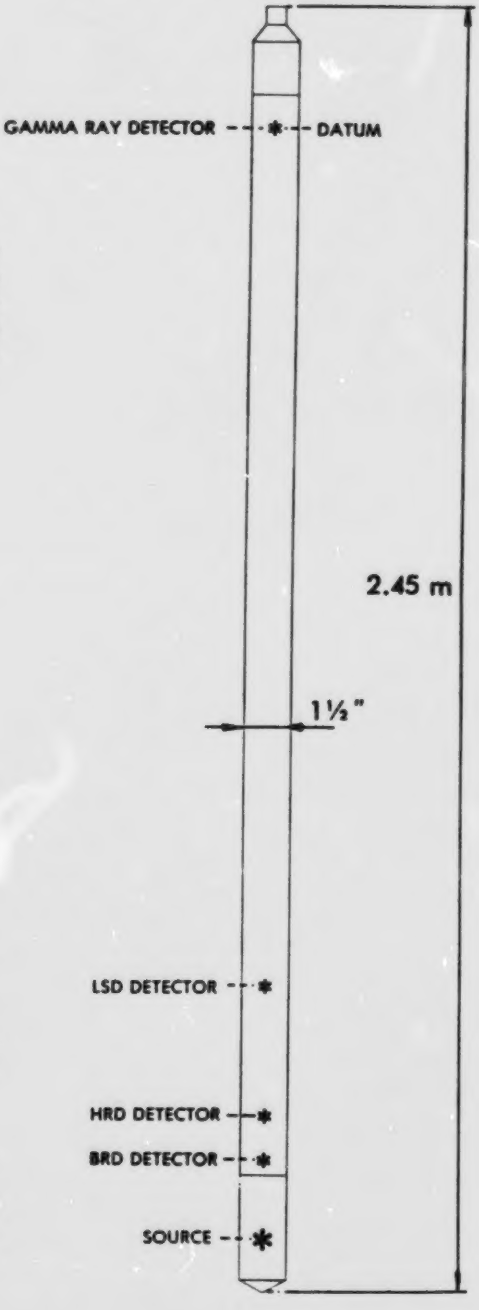
1. BPB Coal Interpretation Manual
2. The Radiation Density Log Applied to the Resolution of Thin Beds in Coal Measures — J. R. Samworth
3. Slimline Dual Detector Density Logging, a Semi-Theoretical but Practical Approach to Correction and Compensation — J. R. Samworth

DD2 DUAL DENSITY, GAMMA RAY, SONDE.

(OR COAL TRI-SONDE)

MEASUREMENTS:

LONG SPACING DENSITY (LSD)
BED RESOLUTION DENSITY (BRD)
or HIGH RESOLUTION DENSITY (HRD)
GAMMA RAY



The DD2 Sonde has been designed as a specialist alternative to the more universal DD1, for use in more restricted diameters and/or for logging through casing or drill rods. It is a 3 channel device offering the option of either a 'BRD' or an 'HRD' measurement as the higher resolution density log.

GENERAL SPECIFICATIONS:

Length — 2.45 m (8')
Weight — 14 kg (30 lbs)
Diameter — 3.8 cm (1½")
Temperature — up to 70°C (158°F)
Pressure — up to 210 kg/cm³ (3000 p.s.i.)

OPERATING CONDITIONS:

Hole Depth	— to a max of approx.	2000 m (6500')
Hole Diameter	— open hole:	6 to 20 cm (2½" to 8")
	— casing or rods:	5 to 20 cm (2" to 8")
Logging Speed	— standard logging:	9 m/min (30'/m)
	— detail logging:	2.25 m/min (7.5'/m)
Logging Mode	— free running	

The DD2 Sonde can provide good basic logging in difficult borehole conditions which may preclude the use of the DD1 sonde. Environments may include dry or fluid filled holes and logging may proceed in open hole, through casing (conventional or plastic) or through the drill rods, as formation stability problems dictate.

TECHNICAL INFORMATION:

GAMMA RAY — Measurement of naturally occurring radioactivity utilizes an identical system to that incorporated in the DD1 Sonde.

DENSITY — The principle of operation remains as described in the DD1 leaflet, although the overall systems do differ in some significant ways, specifically:

- — both density channels operate without collimation of either the source or detectors, i.e. measurements utilize a full 360° window around the borehole wall,
- — the sonde operates in a 'free running' mode, as opposed to the caliper controlled 'sidewall' configuration of the DD1.

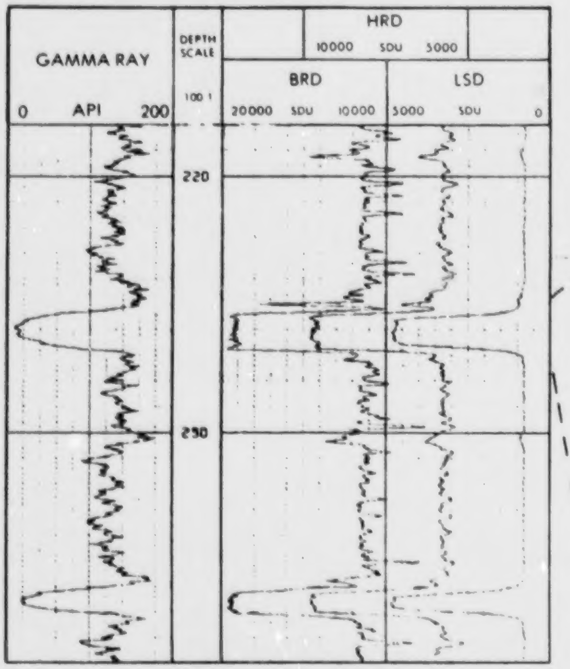
LSD — A source to detector spacing of 48 cm (19") is maintained.

BRD (or HRD) — The standard mode of operation offers a 15 cm (6") spacing BRD log as the higher resolution density channel, although the option exists for this to be modified to a 24 cm (9.5") HRD measurement as required.

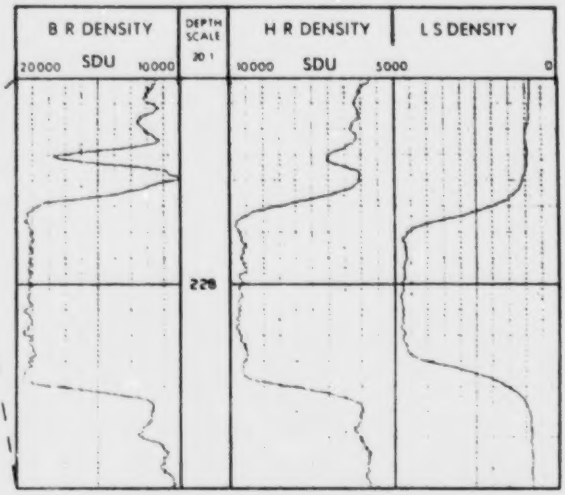
SOURCE — A doubly encapsulated sealed source of Caesium 137 at an activity of 50 mCi, is mounted within a holder securely locked to the sonde during logging operations. This source holder is transported in a purpose designed shield with a surface radiation level less than 7 mrem/hr.

PRESENTATION:

Metric or Imperial scale logs may be presented on any API based format. 'General' scales range from 100:1 upward whilst 'Detail' scales, reserved for closer investigation of zones of interest, are available down to 10:1.



General Scale Lithology Logging



Detail Scale Seam Evaluation

APPLICATION SUMMARY:

The DD2 provides a basic single run Gamma/Density evaluation package, primarily for application where borehole conditions preclude use of the DD1.

GAMMA RAY — Shale content, Lithology identification and Correlation
DENSITY : LSD — Lithology identification and Correlation, Porosity indicator
: BRD (or HRD) — More precise boundary definition and seam thickness evaluation

REFERENCES:

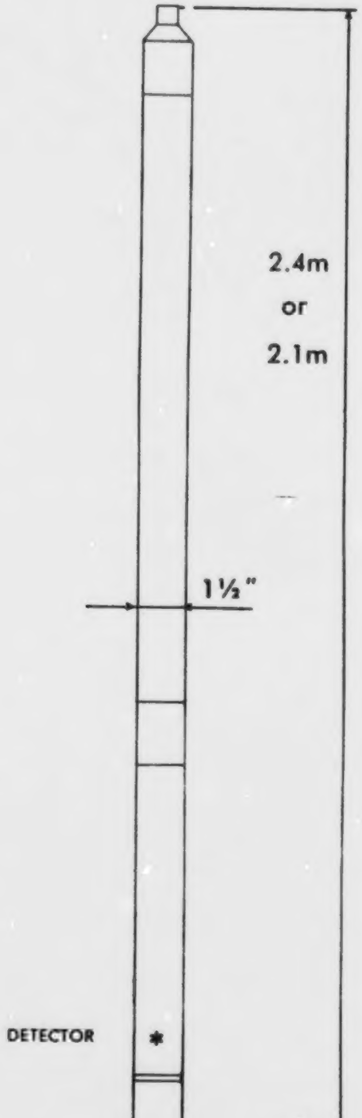
Further information may be found in: The DD1 Sonde — Subsurface leaflet No. 1

NO1 NEUTRON SONDE

MEASUREMENTS:

LONG SPACING NEUTRON	(LSN)
or SHORT SPACING NEUTRON	(SSN)

The NO1 single function sonde provides Neutron log options in all ranges of borehole conditions generally associated with slimhole drilling. Long Spacing based porosity logging is standard although a Short Spacing option can be made available for higher resolution work in better quality boreholes.



GENERAL SPECIFICATIONS:

Length	— Long spacing mode 2.41m (8') — Short spacing mode 2.13m (7')
Weight	— 11Kg (24lbs)
Diameter	— 3.8cm (1.5")
Temperature	— up to 70°C (158°F)
Pressure	— up to 210kg/cm² (3000) psi

OPERATING CONDITIONS:

Hole Depth	— to a max. of approx. 2000m (6500')
Hole Diameters	— open hole: 6.0 to 30cm (2.5 to 12") — casing or rods: 5.0 to 30cm (2.0 to 12")
Logging Speeds	— standardly 9m/min (30'/min) — detail logging 2.25m/min (7.5'/min)
Logging Mode	— free running

Porosity calibration is based on the Long Spacing option and requires that logging be performed in open, fluid filled boreholes; although valuable qualitative logs may also be obtained from Long or Short Spacing logs in dry holes and through casing or drill rods.

Although less effected by borehole rugosity than most other slimhole tools, the Neutron log will, even in its long spacing form, be adversely affected by excessive caving.

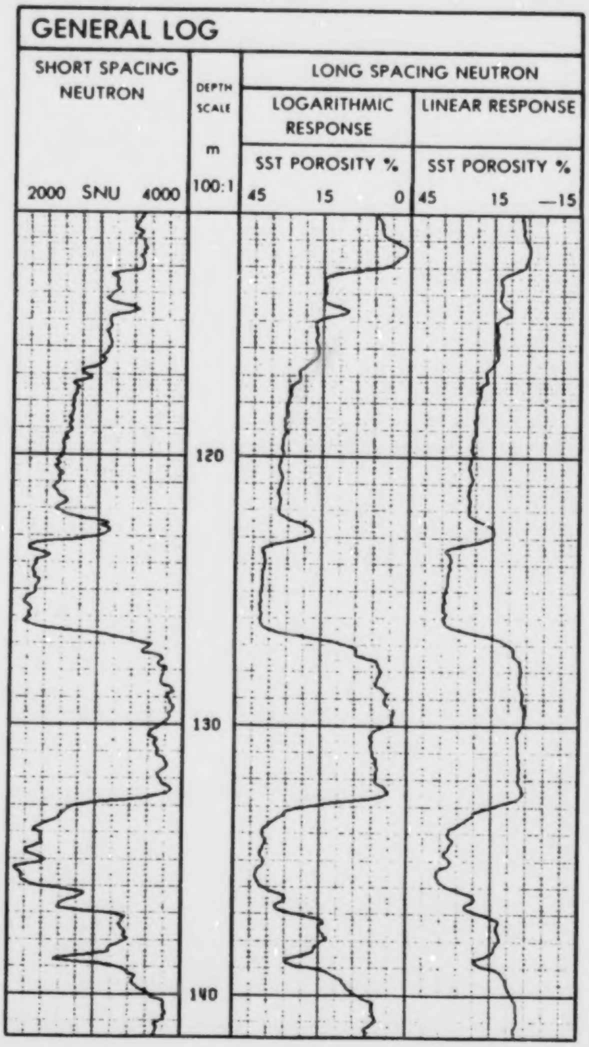
TECHNICAL INFORMATION:

The Neutron log is essentially a measurement of the ability of the formation to thermalise (slow down) high energy neutrons as emitted from the logging source. Being a function of the presence of lighter elements (primarily hydrogen) this log, after correction for borehole effects, may be presented as an Index of Hydrogen and/or in turn as a measurement of Formation Porosity.

High energy Neutrons are emitted with a 360° window from the logging source attached respectively 44cm (Long Spacing) or 25cm (Short Spacing alternative) beneath the uncollimated $Helium_3$ detector tube. Calibration utilises portable passive jigs to allow log presentation in porosity units.

SOURCE — a double encapsulated sealed source of Americium 241/Beryllium at an activity of One Curie is mounted in a stainless steel holder and locked securely to the sonde during logging operations. The source holder is transported in a purpose designed shield with a maximum surface radiation level of 2 mR/hr (gamma) and 6 mR/hr (Neutron).

PRESENTATION:



The Long Spacing Neutron porosity log is standardly presented with a logarithmic response emphasising the Lower porosity range, with a linear response option available after further processing. Both LSN and SSN logs are available with a full flexibility of scales and formats on the API grid.

APPLICATIONS:

LONG SPACING NEUTRON — Lithology identification and correlation in the full range of open, cased (or thr' drill rods), fluid filled and dry boreholes; with quantitative measurement of porosity allowing formation evaluation in open fluid filled holes.

SHORT SPACING NEUTRON — A 'good hole' alternative to the LSN offering higher vertical resolution for more detailed evaluation.

REFERENCE:

BPB Coal Interpretation Manual.

V01, V02

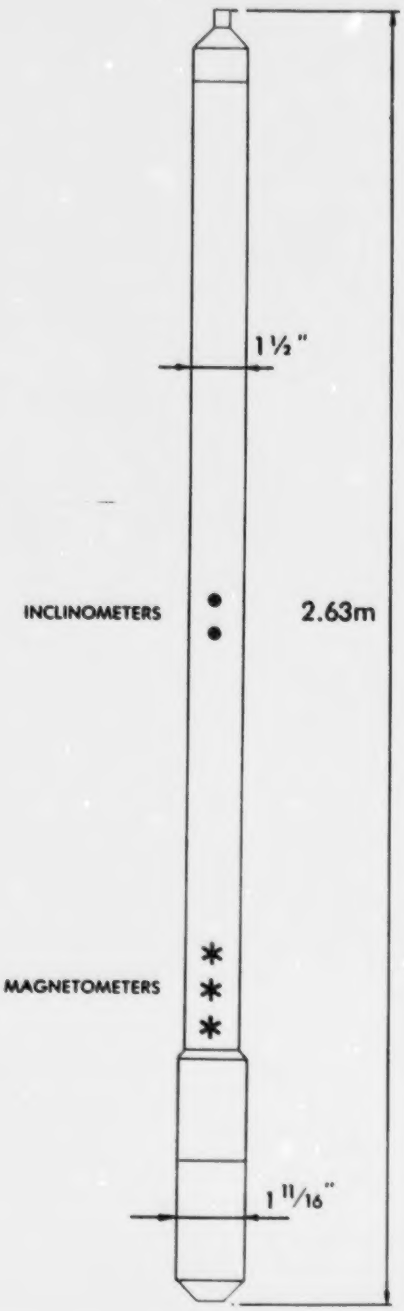
VERTICALITY SONDES

MEASUREMENTS:

HOLE TILT
AZIMUTH OF HOLE TILT
TRUE VERTICAL DEPTH
TRUE HOLE POSITION

The Verticality Sonde provides a full and continuous slimhole directional survey, primarily in open hole environments. Tilt and Azimuth data are recorded throughout the logging run with further processing adding True Depth and Position with respect to the upper reference point (surface or casing shoe). Additional options offer a more comprehensive evaluation and graphical presentation of all output.

Two versions are offered: V01 being the standard with V02 offering measurement over a larger range of hole tilt angles.



GENERAL SPECIFICATIONS:

Length — 2.63m (8.6')
Weight — 10kg (22lbs)
Diameter — 4.2cm (1.7") max
Temperature — up to 70°C (158°F)
Pressure — up to 210kg/cm² (3000 p.s.i.)

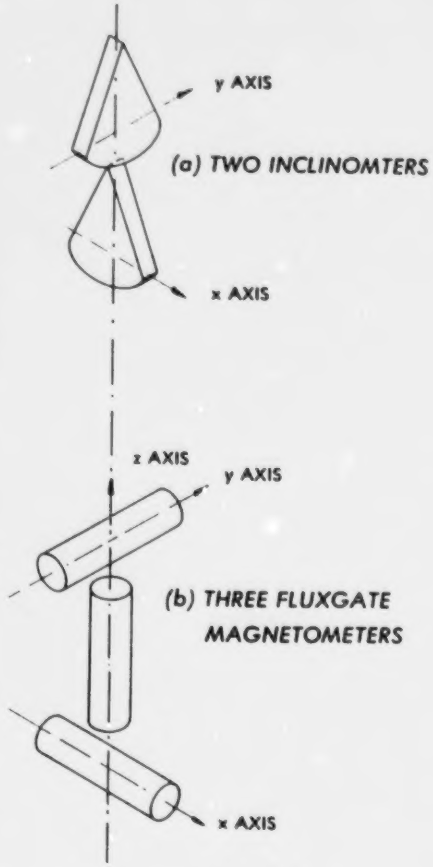
OPERATING CONDITIONS:

Hole Depth — to a max of approx. 2000m (6500')
Hole Diameter — open hole: 6.5 to 30cm (2.5" to 12")
Logging Speed — standardly: 9m/min (30'/min)
Logging Mode — free running

The Verticality Sonde functions equally well in both fluid filled and dry boreholes. It is primarily an open hole survey tool, the use of magnetometer transducers prevents the acquisition of azimuth data (and hence calculation of hole position) through conventional casing or drill rods. This survey is largely unaffected by even quite serious caving in slimhole environments.

TECHNICAL INFORMATION:

Five transducers in fixed alignment on the three axes of the sonde enable continuous monitoring of it's orientation. The diameter constraints associated with slimline tool design call for a solid state approach to transducer design, in contrast to the much larger electro-mechanical devices incorporated in conventional oilfield systems.



Two inclinometers define the sonde's minor (x and y) axes (fig. 1a) and provide measurement of both the borehole tilt with respect to vertical and of the direction of tilt with respect to a 'reference'.

Three fluxgate magnetometers mounted on the sonde's (x, y and z) axes (fig. 1b) add a knowledge of the rotational orientation of the sonde and, in conjunction with the tilt measurement, provide measurement of the azimuth of the 'reference' with respect to Magnetic North.

Hence: Tilt w.r.t. Vertical and Azimuth of Tilt w.r.t. Mag.N (or True N with the input of the local angle of declination)

Fig. 1 Transducer Schematic.

Calibration is performed regularly in a mechanical jig facility backed up with simple field checks made directly before and after the logging of each hole.

The outputs of all five transducers are transmitted for continuous surface recording throughout the logging run,during which they are translated into spot readings of Tilt and Azimuth as a function of log depth.

Various processing options are available upon completion of the logging run to provide True Vertical Depth and True Hole Position as functions of log depth and w.r.t. surface or casing shoe.

Each sonde is standardly set for:

V01 — range 0 to 20°, the standard option for nominally vertical holes with accuracies of ± ½° on inclination and ± 10° on azimuth,

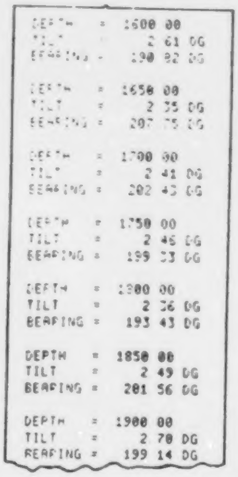
V02 — range 0 to 40°, with accuracies of ± 2° on inclination and ± 10° on azimuth,

although in certain circumstances either sonde may be retuned to provide increased accuracy over a decreased range of inclination.

PRESENTATION:

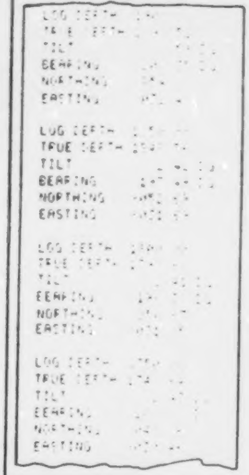
Two forms of output are available, both of which can be set for either metric or imperial units.

(A) VIA LOG PROCESSOR. Hole survey result listings are presented automatically on a fixed 10m (or 50 ft) log depth incremental basis.



```
DEPTH   =  1600 00
TILT    =     2 61 DG
BEARING =   190 82 DG

DEPTH   =  1650 00
TILT    =     2 35 DG
BEARING =   207 75 DG

DEPTH   =  1700 00
TILT    =     2 41 DG
BEARING =   202 43 DG

DEPTH   =  1750 00
TILT    =     2 46 DG
BEARING =   199 33 DG

DEPTH   =  1800 00
TILT    =     2 36 DG
BEARING =   193 43 DG

DEPTH   =  1850 00
TILT    =     2 49 DG
BEARING =   201 56 DG

DEPTH   =  1900 00
TILT    =     2 70 DG
BEARING =   199 14 DG
```

Fig. 2a. Listing created during the logging run, of Tilt and Azimuth w.r.t. Magnetic or True North (Bearing) as a function of log depth.



```
LOG DEPTH  [illegible]
TRUE DEPTH [illegible]
TILT       [illegible]
BEARING    [illegible]
NORTHING   [illegible]
EASTING    [illegible]

LOG DEPTH  [illegible]
TRUE DEPTH [illegible]
TILT       [illegible]
BEARING    [illegible]
NORTHING   [illegible]
EASTING    [illegible]

LOG DEPTH  [illegible]
TRUE DEPTH [illegible]
TILT       [illegible]
BEARING    [illegible]
NORTHING   [illegible]
EASTING    [illegible]

LOG DEPTH  [illegible]
TRUE DEPTH [illegible]
TILT       [illegible]
BEARING    [illegible]
NORTHING   [illegible]
EASTING    [illegible]
```

Fig. 2b. Listing created on completion of the logging run adds true depth and hole position w.r.t. the upper reference point.

(B) VIA COMPUTER GRAPHICS UNIT. Provides full graphical analysis of hole survey data as well as more comprehensive listings of hole position in both Axial and Polar co-ordinates. Other advantages of this approach include:

— error analysis on hole position

— presentation scale flexibility

— cross sections selectable at any specified depth

— facility to join data from separate logging runs

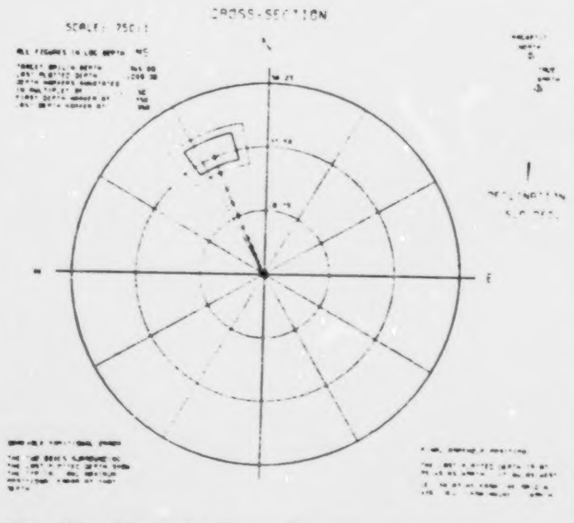


Fig. 3a Borehole Cross Section, Plan View of the Full Logged Interval.

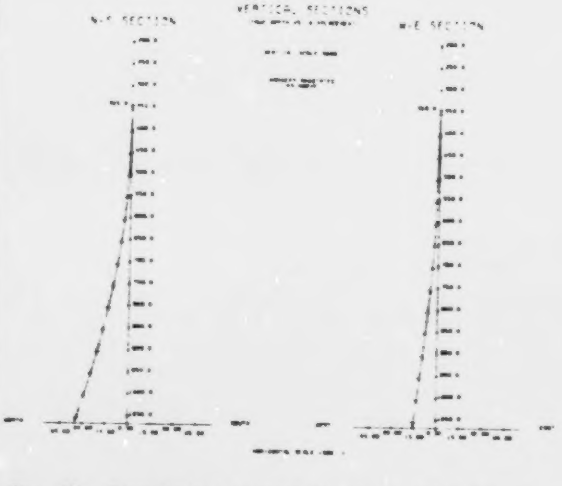


Fig. 3b Borehole Vertical Sections, Side View of the Full Logged Intervals in N-S and W-E vertical planes.

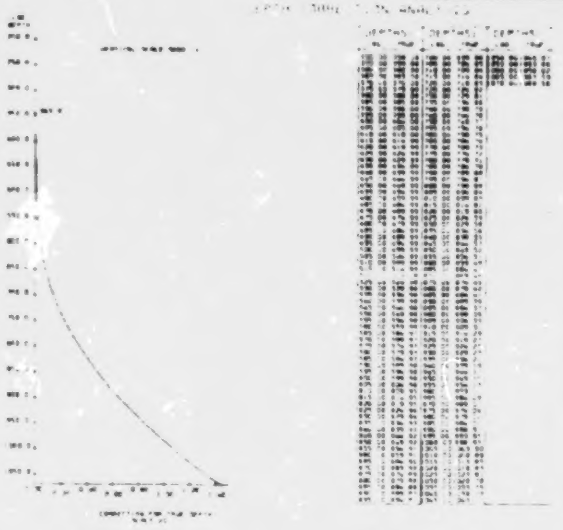


Fig. 3c Depth Correction Analysis in graphical and tabulated form.

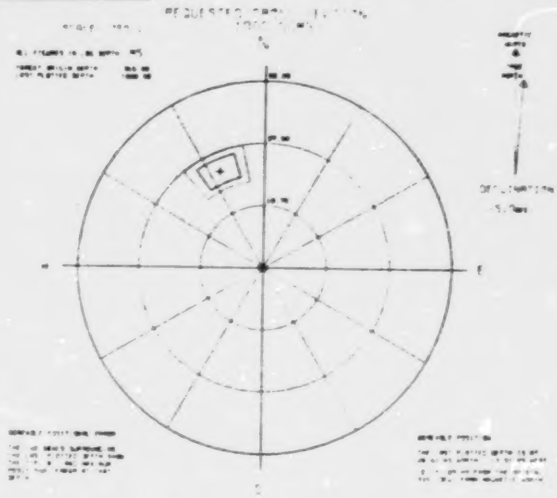


Fig. 3d Requested Cross Section at any specified depth.

```
                                   Verticality Data Listing                             Date processed: 26-APR-83
                            All co-ordinates with respect to Magnetic North
      DEPTHS               BOREHOLE       AXIAL CO-ORDS.     POLAR                      POLAR ERROR CO-ORDINATES (maximum & typical)
   log         true        tilt  AZI      North      East   brng radius           brng radius  brng radius  brng radius  brng radius

350.00        350.00       0.7   293.      0.03     -0.04   300.     0.05         300     0.09  296.   0.01  300.   0.08  299.    0.02
355.00        355.00       0.7   293.      0.05     -0.10   297.     0.11         298.    0.20  295.   0.02  298.   0.17  297.    0.05
360.00        360.00       0.6   290.      0.08     -0.15   297.     0.17         297.    0.30  296.   0.04  297.   0.25  296.    0.08
365.00        365.00       0.7   300.      0.10     -0.20   296.     0.22         297.    0.40  296.   0.05  297.   0.34  296.    0.11
370.00        370.00       0.8   293.      0.12     -0.25   296.     0.28         296.    0.50  295.   0.07  296.   0.43  296.    0.14
375.00        375.00       0.7   292.      0.15     -0.31   295.     0.35         295.    0.61  294.   0.09  295.   0.52  295.    0.17
380.00        380.00       0.6   297.      0.17     -0.37   295.     0.41         295.    0.71  294.   0.11  295.   0.61  295.    0.21
385.00        385.00       0.6   306.      0.20     -0.42   296.     0.46         296.    0.61  295.   0.12  296.   0.70  295.    0.23
390.00        390.00       0.5   304.      0.23     -0.46   296.     0.51         296.    0.91  295.   0.12  296.   0.77  296.    0.25
395.00        295.00       0.7   302.      0.26     -0.52   297.     0.58         297.    1.01  296.   0.14  247.   0.87  297.    0.29
400.00        400.00       0.7   308.      0.30     -0.57   298.     0.64         298.    1.12  298.   0.17  298.   0.96  298.    0.33
```

Fig. 3e Full Data Listings

APPLICATION SUMMARY:

Hole surveying becomes particularly important in mine or production planning, where it is essential to understand the actual performance of any borehole as it relates to the real positions and true depths of intersection with specific horizons. The importance of such information increases with depth as borehole performance assumptions can become significantly and increasingly inaccurate.

REFERENCES:

NB — The Verticality Sonde can be run alone or in conjunction with an attachable microresistivity/caliper section to create the Dipmeter Sonde. Here Verticality data continues to provide this full hole survey as well as enabling the measured strata dip to be referenced to the horizontal and it's direction orientated w.r.t. Magnetic or True North (see Leaflet Subsurface No. 9).

Further details of the Verticality service may be found in the following BPB publications available on request:

1. BPB Coal Interpretation Manual
2. Slimhole Dipmeter — R W Wroot

DV1, DV2

DIPMETER SONDES

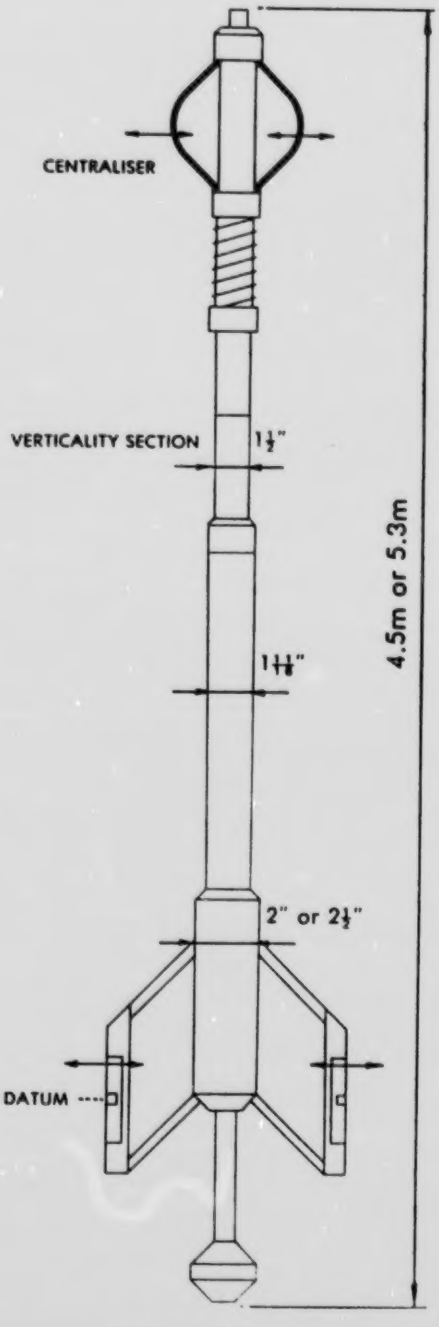
(INCLUDES THE VERTICALITY SONDE)

MEASUREMENTS:

FORMATION DIP — MAGNITUDE
— AZIMUTH

HOLE VERTICALITY — output as per Verticality Sonde, see leaflet: Subsurface No. 8.

The Dipmeter Sonde is a 3 arm device designed to measure formation dip, and provide a complete hole survey, in nominally vertical or slightly deviated slimline boreholes. Two versions are offered: DV1 being the standard with DV2 a slightly larger version providing increased sidewall thrust for use at higher degrees of borehole tilt, at larger diameters or in more rugous boreholes.



GENERAL SPECIFICATIONS:

		DV1	DV2
Length	—	4.5m (14.8') :	5.3m (17.4')
Weight	—	24.5kg (54lbs) :	36.0kg (79lbs)
Diameter	—	5.1cm (2") :	6.4cm (2½")
Temperature	—up to 70°C (158°F)		
Pressure	—up to 210kg/cm² (3000 psi)		

OPERATING CONDITIONS:

Hole Depth — to a max. of approx. 2000m (6500')
Hole Diameter — open hole, DV1: 7.5 to 20cm (3 to 8")
DV2: 10.0 to 25cm (4 to 10")
Logging Speed — 4m/min (13'/min)
Logging Mode — centralized by the 3 caliper arms, aided in larger diameters by a passive guide system mounted on the upper section.

Formation dip can only be measured in open, fluid filled boreholes. Optimum results will be seen in small diameter boreholes (6" or less), with good caliper and with mud resistivities in the approximate range of 1 to 10 ohm metres. The DV1 Sonde will operate up to borehole tilts of

TECHNICAL INFORMATION:

The Dipmeter Sonde is designed to enable identification and measurement of offsets in the depths of features as seen by three detector pads, spaced around the borehole wall with 120° angular separation. Addition of pad direction and hole caliper data enables translation of these offsets into a measurement of 'Apparent' dip, i.e. dip with respect to the borehole. Conversion to 'True' dip may then be achieved by correcting for the effects of hole tilt, allowing presentation of Dip Magnitude w.r.t. the Horizontal and Dip Direction w.r.t. North.

The three circumferential measurements are made by caliper mounted microfocussed resistivity pads, assembled beneath an orientation sub section — the Verticality Sonde when run alone as a hole survey device. Sonde assembly aligns pad 1 into the x-axis of the verticality section (see leaflet No. 8) to allow orientation of the dip plane and presentation of True Dip, irrespective of hole tilt or sonde rotation, see ref. 2.

The caliper system is motor controlled, being held closed for borehole entry and activated into a spring loaded open position prior to the logging run. This provides both borehole diameter and pad pressure for sidewall resistivity measurement. The resistivity logs are recorded with ultra high vertical resolution (0.5cm sense electrode) and shallow investigation (hence the importance of minimising borehole caving), both essential for good dip measurements.

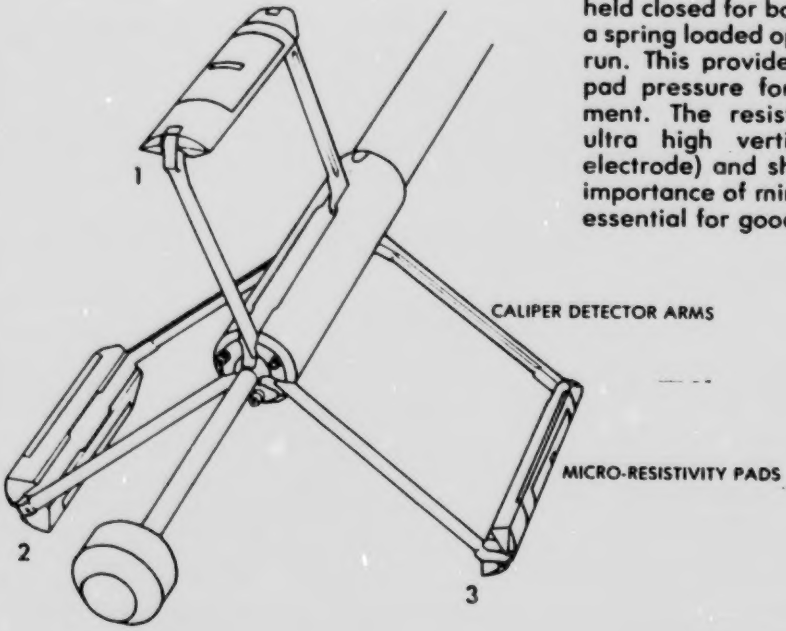


Fig. 1 Pad and Arm Detail

In operation the Dipmeter Sonde transmits 9 channels of data for surface recording on magnetic tape as continuous depth based logs.

In summary:

$$\left.\begin{array}{l} 3 \times \text{microfocussed resistivities} \\ 1 \times \text{caliper} \\ \left.\begin{array}{l} 2 \times \text{inclinometers} \\ 3 \times \text{magnetometers} \end{array}\right\} \text{Verticality Sonde} \end{array}\right\} \text{Dipmeter Sonde}$$

Field presentation consists primarily of displaying the resistivity logs and monitoring all other data channels, to ensure that adequate quality data is available to the subsequent interpretation system. The quantity of data involved and the nature of the processing inevitably defines the need for a computer based approach to interpretation and result presentation.

PRESENTATION:

Dipmeter logging offers all of the hole survey analysis options described in leaflet No. 8 in addition to the evaluation of formation dip illustrated below. Both Metric and Imperial data can be processed, with results available on a full variety of vertical scales.

Fig. 2 is an example of the final 'tadpole plot' output of the computer package, implementation of which requires the selection of certain interpretation parameters. The following notes summarize the process and describe the illustrated output, although comprehensive discussions are a little beyond the scope of this 'sonde' leaflet.

At the heart of the interpretation is computer matching of sections of the three resistivity curves, to determine offsets between pads 1 — 2 and 1 — 3. Such 'correlations' are graded up to a maximum value of 1.0, this grading remaining as a measure of confidence in the resulting calculation of dip at that depth.

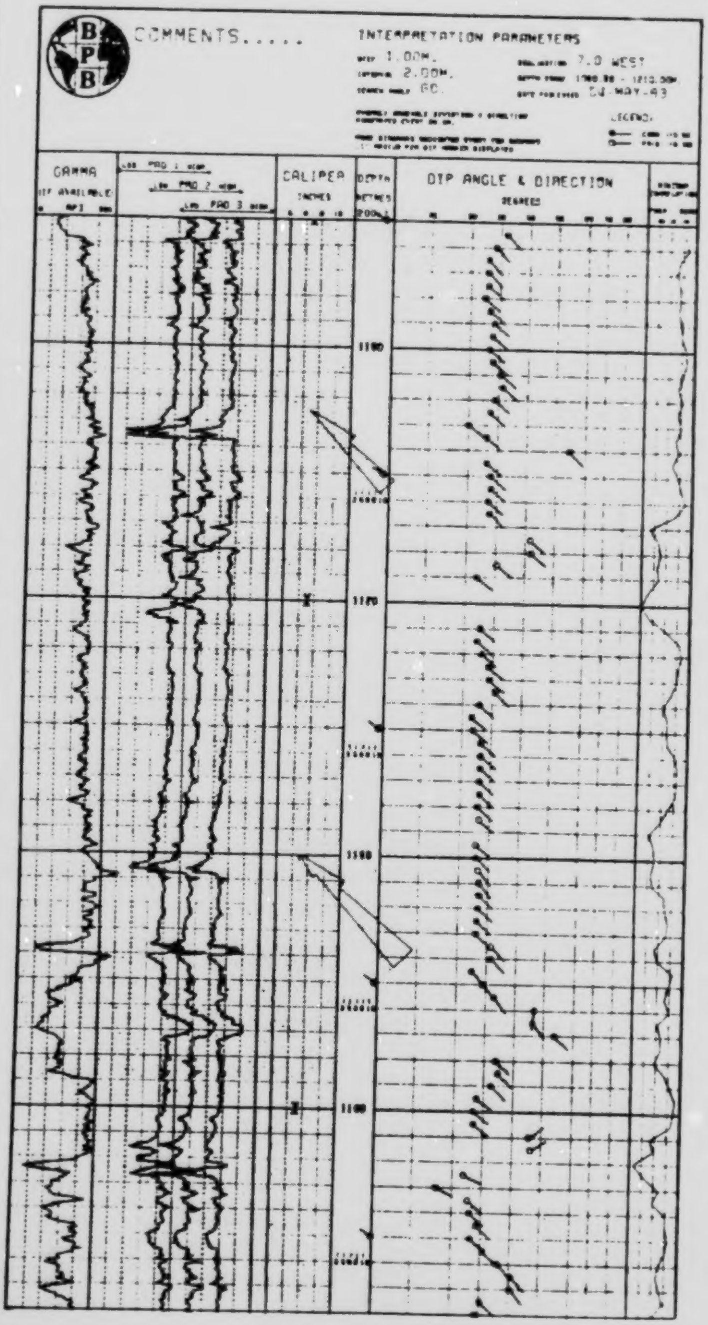


Fig. 2 Dipmeter Interpretation. Standard Output

TRUE DIP MAGNITUDE
— is indicated w.r.t. Horizontal by the position of the tadpole body.

TRUE DIP DIRECTION
— is indicated by the direction of the tail of the tadpole, True North being represented by a vertically upward pointing tail.

BOREHOLE TILT
— both tilt and its azimuth are indicated by slightly larger tadpoles, presenting averaged values periodically in the depth margin.

Step, Interval, Search Angle and Declination Angle are all selectable options defining the way in which interpretation is to proceed:

STEP
— is the distance between successive correlation depths.

INTERVAL
— is the length of Pad 1 curve used in each correlation.

SEARCH ANGLE
— is the maximum formation dip for which the program is allowed to search.

DECLINATION ANGLE
— is the local relationship between Magnetic and True North, input to allow presentation of directions w.r.t. True North.

A Gamma Ray log is plotted with the three resistivity curves to assist formation identification and correlation.

The Caliper log is presented as a monitor of hole condition.

'Rose Diagrams' or dip azimuth frequency plots are presented on a periodic basis through sections of the borehole as arrowed.

Minimum correlations are plotted to illustrate the value of the poorest of the two pad curve correlations (1 — 2 and 1 — 3) made for each dip calculation. The minimum correlation value also defines the presentation of dip according to the criteria listed in the legend:

Solid tadpoles represent 'good' or high confidence dips, and open tadpoles represent 'fair' or medium confidence dips, with 'poor' or low confidence dips left out of the final plot.

This criteria is determined during a preliminary phase (output not illustrated), during which all correlations are presented irre-

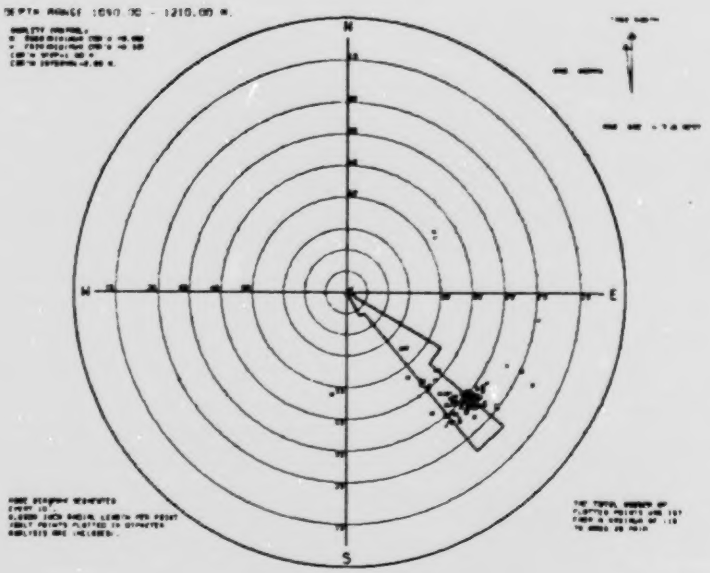


Fig. 3
As an optional extra presentation this Dipmeter Point Distribution Analysis illustrates the frequency distribution of both dip magnitude and azimuth over any specified depth interval(s).

```
                        Magnetic declination  7.00 degrees West of North                                                    04-MAY-83
                        Correlation step  1.00 metres .Interval  2.00 metres  Search angle 60. degrees                      PAGE    1

 DEPTH   CAL. BOREHOLE FORMATION  MIN.      DEPTH   CAL. BOREHOLE FORMATION  MIN.      DEPTH   CAL. BOREHOLE FORMATION  MIN.
 metres  ins. TILT AZI  DIP  AZ.  COR      metres  ins. TILT AZI  DIP  AZI  COR.      metres  ins. TILT AZI  DIP  AZI  COR.

1091.00  3.9   9.8 303. 32.4 130. 0.78    1092.00  3.9   9.8 303. 29.4 130. 0.85    1093.00  3.9   9.8 303. 26.8 140. 0.67
1094.00  3.9   9.8 303. 26.5 134. 0.63    1095.00  3.9   9.8 303. 26.0 132. 0.69    1096.00  3.9   9.9 303. 25.5 132. 0.70
1097.00  3.9   9.9 303. 27.5 130. 0.69    1098.00  4.0   9.9 303. 29.1 128. 0.73    1099.00  3.9   9.9 303. 28.6 129. 0.74
1100.00  3.9   9.9 303. 27.5 130. 0.83    1101.00  3.9   9.9 303. 28.0 129. 0.86    1102.00  3.9   9.9 303. 30.0 130. 0.76
1103.00  3.9   9.9 303. 31.5 131. 0.72    1104.00  3.9   9.9 303. 29.9 131. 0.70    1105.00  3.9  10.0 304. 20.3 131. 0.69
1106.00  3.9  10.0 304. 20.1 127. 0.77    1107.00  4.0  10.0 304. 27.1 131. 0.67    1108.00  4.0  10.1 304. 55.2 135. 0.71
1109.00  3.9  10.1 304. 27.2 130. 0.59    1110.00  3.9  10.1 304. 28.7 132. 0.71    1111.00  3.9  10.2 304. 28.9 131. 0.70
1112.00  3.9  10.2 304. 20.0 131. 0.87    1113.00  3.9  10.2 304. 28.7 135. 0.66    1114.00  3.9  10.2 304. 30.1 130. 0.17
1115.00  4.0  10.3 305. 41.9 129. 0.35    1116.00  3.9  10.3 305. 42.3 131. 0.40    1117.00  3.9  10.3 305. 30.6 129. 0.33
1118.00  4.0  10.4 305. 24.3 128. 0.35    1119.00  4.0  10.4 305. 23.1 135. 0.15    1120.00  4.0  10.4 305. 31.9 303. 0.01
1121.00  4.0  10.4 305. 26.8 130. 0.20    1122.00  4.0  10.4 305. 26.1 130. 0.53    1123.00  4.0  10.4 305. 25.1 131. 0.79
1124.00  4.0  10.4 305. 27.1 131. 0.84    1125.00  4.0  10.4 305. 29.5 129. 0.77    1126.00  4.0  10.5 305. 29.9 129. 0.76
1127.00  4.0  10.5 305. 31.2 136. 0.65    1128.00  4.0  10.5 305. 26.4 130. 0.50    1129.00  4.0  10.5 305. 23.6 129. 0.58
1130.00  4.0  10.5 305. 24.2 130. 0.58    1131.00  4.0  10.6 306. 27.4 131. 0.59    1132.00  4.0  10.6 306. 27.4 130. 0.77
1133.00  4.0  10.6 306. 27.4 130. 0.90    1134.00  4.0  10.6 306. 27.0 130. 0.79    1135.00  4.0  10.7 306. 27.2 132. 0.70
1136.00  4.0  10.7 306. 26.7 132. 0.62    1137.00  4.0  10.7 306. 27.3 132. 0.48    1138.00  4.0  10.7 306. 65.4 130. 0.20
1139.00  4.0  10.7 306. 26.2 129. 0.37    1140.00  4.0  10.7 307. 26.5 137. 0.40    1141.00  4.0  10.7 307. 27.3 143. 0.32
```

Fig. 4
Comprehensive listings presented as part of the standard dipmeter interpretation package.

APPLICATIONS:

The Dipmeter provides structural information and enables apparent formation thicknesses to be corrected for the combined effects of formation dip and hole tilt.

Parameter selection, primarily of the interval, is all important and should be specified in accordance with the required application. Generally speaking long intervals will reveal structural dips whereas shorter intervals will be more suitable for the determination of finer details of dip associated with sedimentation studies. 1 to 2m intervals offer a good compromise and are usually used in the first instance.

Inspection of overall trends may often reveal faulting and other important geological features.

REFERENCES:

Further information on the Slimline Dipmeter service may be found in the following BPB publications, available on request:

1. BPB Coal Interpretation Manual.
2. Slim Hole Dipmeter — R W Wroot.

TT1 TEMPERATURE SONDE

MEASUREMENTS:

ABSOLUTE TEMPERATURE
TEMPERATURE DIFFERENCE
TEMPERATURE DIFFERENTIAL

The TT1 Sonde provides an absolute temperature profile as a function of borehole depth, highlighting local anomalies through closer inspection of the temperature changes seen. For optimum results the borehole should be allowed to stand for 12-24 hours prior to temperature logging.

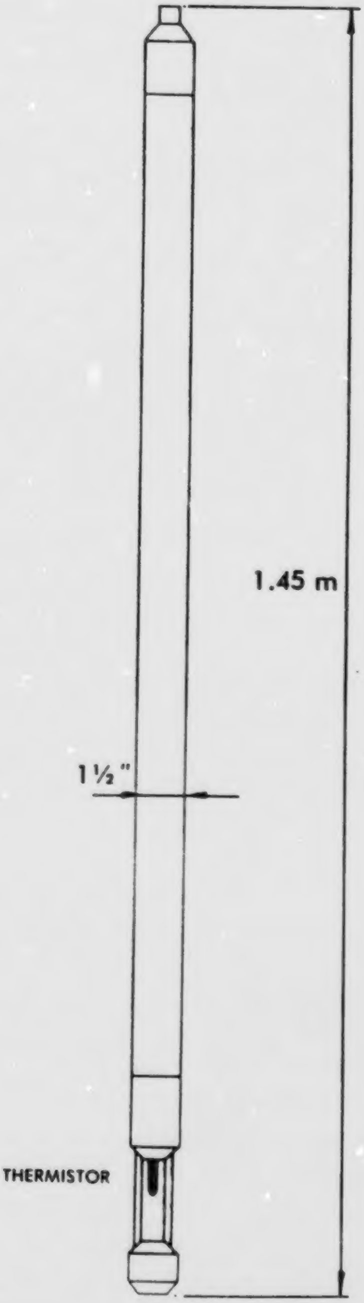
GENERAL SPECIFICATIONS:

Length — 1.45 m (5.5')
Weight — 11 kg (24lb)
Diameter — 3.8 cm (1½")
Temperature — up to 100°C (212°F)
Pressure — up to 210 kg/cm^2 (3000 psi)

OPERATING CONDITIONS:

Hole Depth — to a max of approx. 2000 m (6500')
Hole Diameter — min. 6 cm (2.5"), no maximum
Logging Speed — 9 m/min (30'/min)
Logging Mode — free running, log recorded on entry into borehole

Optimum logging requires that the formations and borehole fluid have been allowed to reach temperature stabilisation before logging begins. Furthermore for this same reason the temperature log should be the first tool into the borehole, and data should be recorded during the entry rather than exit run. The sonde will function in any borehole conditions although open, fluid filled conditions are needed to achieve the formation temperature monitoring usually required.



TECHNICAL INFORMATION:

All three log options are derived simultaneously from measurement of the electrical resistance of a single Thermistor, mounted in a protecting cage at the base of the sonde. Being a calibrated function of temperature this resistance measurement is presented as an absolute temperature log, with optional processing available to look more closely at the nature of the more rapid changes encountered. Specifically:

ABSOLUTE TEMPERATURE
— Borehole temperature seen by the sonde as a function of depth. This is the fundamental temperature log and is needed to properly evaluate any of the other options selected.

TEMPERATURE DIFFERENCE
— is an amplification of features seen on the Absolute log, with rapid changes stripped from the general background Temperature Gradient and presented on a more sensitive scale.

TEMPERATURE DIFFERENTIAL
— is a presentation of the Absolute log differentiated with respect to time. This can be related, through the constant logging speed, to the rate of change of temperature with depth.

PRESENTATION:

Logs may be presented on a variety of metric or imperial vertical scales as required, with the following maximum sensitivities available for the display of each log:

(a) ABSOLUTE — 0.25°C/minor division
(b) DIFFERENCE — 0.25°C/minor division
(c) DIFFERENTIAL — 0.0025°C/sec/minor division

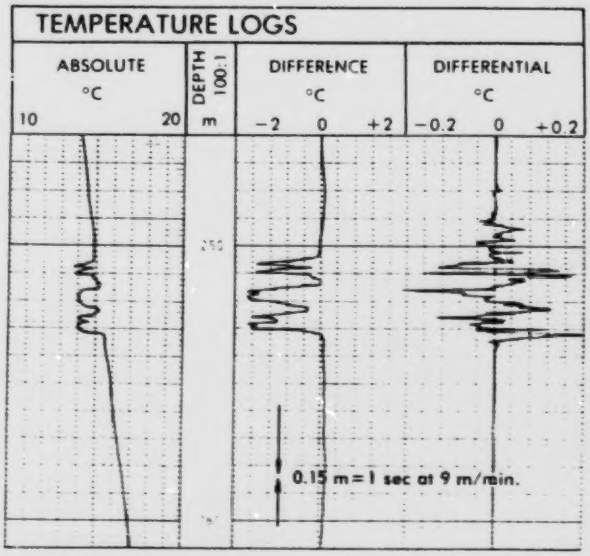


Fig. 1 Presentation Example

APPLICATION SUMMARY:

Temperature logs are used for a variety of purposes, most commonly including:
ABSOLUTE LOGS — Formation temperature for underground-mine planning.
— As an aid to interpretation and correction of other logs, particularly resistivity logs.
DIFFERENTIAL — To identify and help quantify aquifers and fluid flows with the borehole.

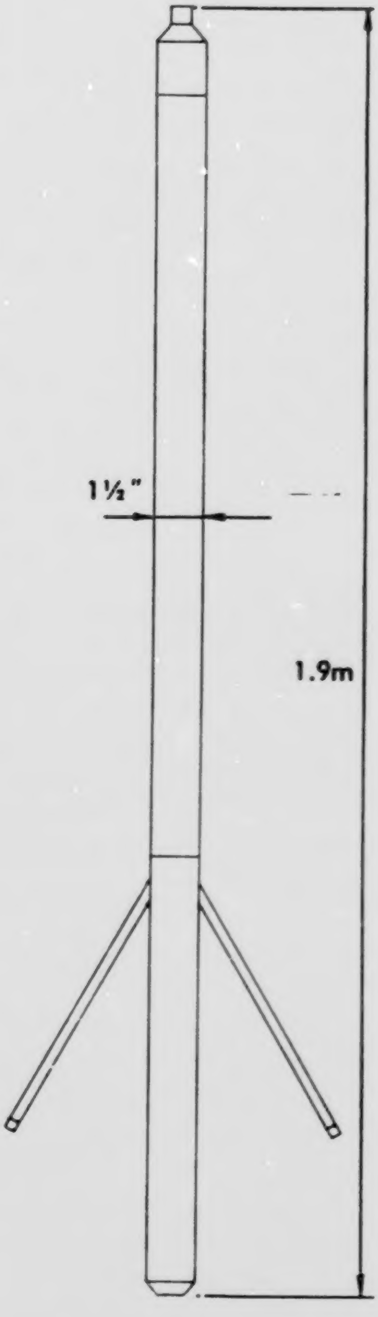
NB: If only the Absolute Bottom Hole Temperature is required it may be more simply obtained by running a BHT insert in conjunction with any other sonde.

CO1 CALIPER SONDE

MEASUREMENT:

HOLE DIAMETER
(AND HOLE VOLUME)

The CO1 Sonde is a specialist 3-arm caliper device. It is designed to provide a more comprehensive measurement of hole size variations than those afforded by single arm and/or pad devices incorporated into other combination tools. Measurement of borehole volume can also be made, as with all other caliper devices, by the integration of the CO1 hole diameter data over the depth interval of interest.



GENERAL SPECIFICATIONS:

Length — 1.90m (6.25')
Weight — 13 kg (28lbs)
Diameter — 3.8 cm (1½")
Temperature — up to 70°C (158°F)
Pressure — up to 210 kg/cm^2 (3000 p.s.i.)

OPERATING CONDITIONS:

Hole Depth — to a max. of approx. 2000m (6500')
Hole Diameter — 5 to 45 cm (2 to 18")
Logging Speed — 9m/min (30'/min)
Logging Mode — centralized by the 3 caliper arms

Logging may proceed in any borehole with a diameter accessible by a 1½" diameter sonde. Requirement will usually be in fluid filled, or dry, open hole conditions.

TECHNICAL INFORMATION:

The 3 arms, held in a 'closed' position for borehole entry, are activated into a spring loaded 'open' configuration prior to commencement of the logging run. This arm extension is achieved by means of a surface controlled motor incorporated within the sonde.

The arms move in unison during the logging run, tracking the average diameter of the borehole. Arm movement is translated, through a rack and pinion and potentiometer system, to an electronic signal for surface transmission and recording. The resulting caliper log is linear with hole diameter and sensitive to the smallest of changes in the borehole wall.

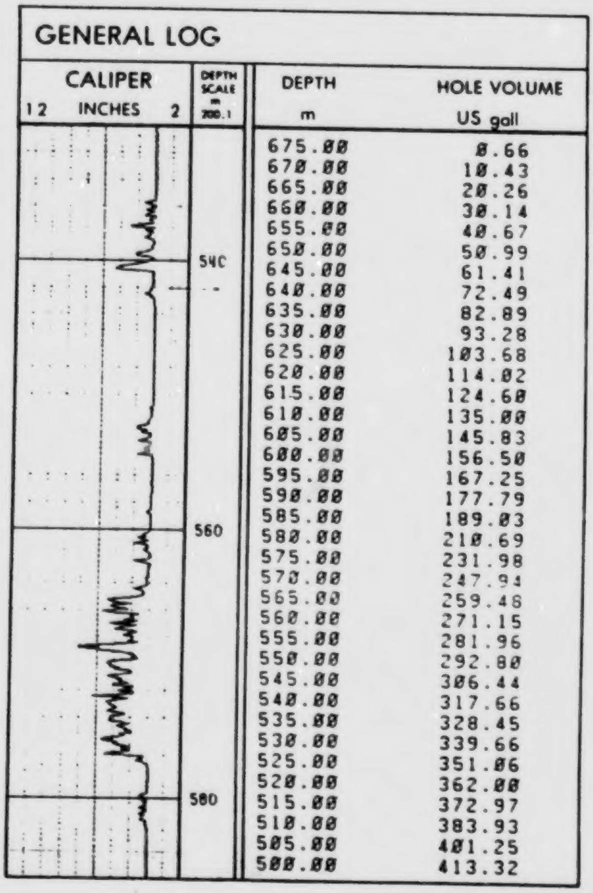
Mechanical calibration, both before and after the logging run, enables accurate presentation of the log in either Metric or Imperial units of hole diameter.

Either 'standard' or 'long' caliper arms, all at $\frac{1}{16}$" diameter with hardened tips to minimise wear, are available to optimise log accuracies over the full operational range.

A log processing option can, by integration of the caliper log, provide a hole volume evaluation.

PRESENTATION:

The Caliper log may be presented on any horizontal and vertical scale in Metric or Imperial units of hole depth and diameter. The curve may be included in a composite presentation with other logs being run, or be presented alone with increased scale sensitivity.



GENERAL LOG

DEPTH m	HOLE VOLUME US gall
675.00	0.66
670.00	10.43
665.00	20.26
660.00	30.14
655.00	40.67
650.00	50.99
645.00	61.41
640.00	72.49
635.00	82.89
630.00	93.28
625.00	103.68
620.00	114.02
615.00	124.60
610.00	135.00
605.00	145.83
600.00	156.50
595.00	167.25
590.00	177.79
585.00	189.03
580.00	210.69
575.00	231.98
570.00	247.94
565.00	259.48
560.00	271.15
555.00	281.96
550.00	292.80
545.00	306.44
540.00	317.66
535.00	328.45
530.00	339.66
525.00	351.06
520.00	362.00
515.00	372.97
510.00	383.93
505.00	401.25
500.00	413.32

APPLICATION SUMMARY:

The CO1 Sonde is recommended when knowledge of borehole wall conditions is considered to be of paramount importance; most often when it is felt that the single arm (DD1, DR1 sondes) or pad (DR1, DV1 sondes) caliper devices, as incorporated in other combination sondes, will not provide an adequate survey.

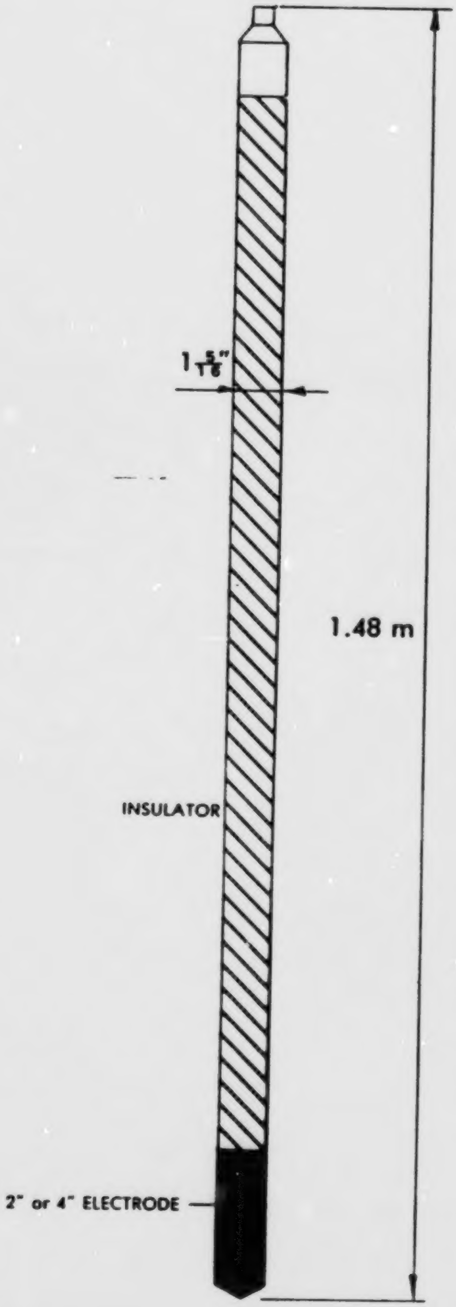
RS1 RESISTANCE, SPONTANEOUS POTENTIAL SONDE

(OR SP/RES SONDE)

MEASUREMENTS:

RESISTANCE (SINGLE POINT)
SPONTANEOUS (OR SELF) POTENTIAL

The RS1 Sonde is a dual function, single electrode, non focussed device producing simultaneous measurement of formation Potential and Resistance.



GENERAL SPECIFICATIONS:

Length — 1.48 m (4.8')
Weight — 6 kg (13 lbs)
Diameter — 3.3 cm (1$\frac{5}{16}$"(
Temperature — up to 70°C (158°F)
Pressure — up to 210 kg/cm^2 (3000 p.s.i.)

OPERATING CONDITIONS:

Hole Depth — to a max. of approx.: 2000 m (6500')
Hole Diameter — open hole: 4 cm to 30+ cm (1.6" to 12+")

Logging Speed — standardly: 9m/min (30'/min)
Logging Mode — free running

Open, fluid filled holes are a prerequisite for both of these electric logs.

Having the lowest replacement value of any BPB sonde, and utilizing no radioactive materials, the RS1 is often used as a first run to assess borehole conditions in unknown or suspect formations.

TECHNICAL INFORMATION:

The Spontaneous Potential (SP) log is a record of the natural electrical potentials developed between the borehole fluid and the surrounding formations. SP's are generated either by electrochemical e.m.f.'s at the junction of dissimilar materials, or by electrokinetic e.m.f.'s developed when fluid moves through a permeable medium.

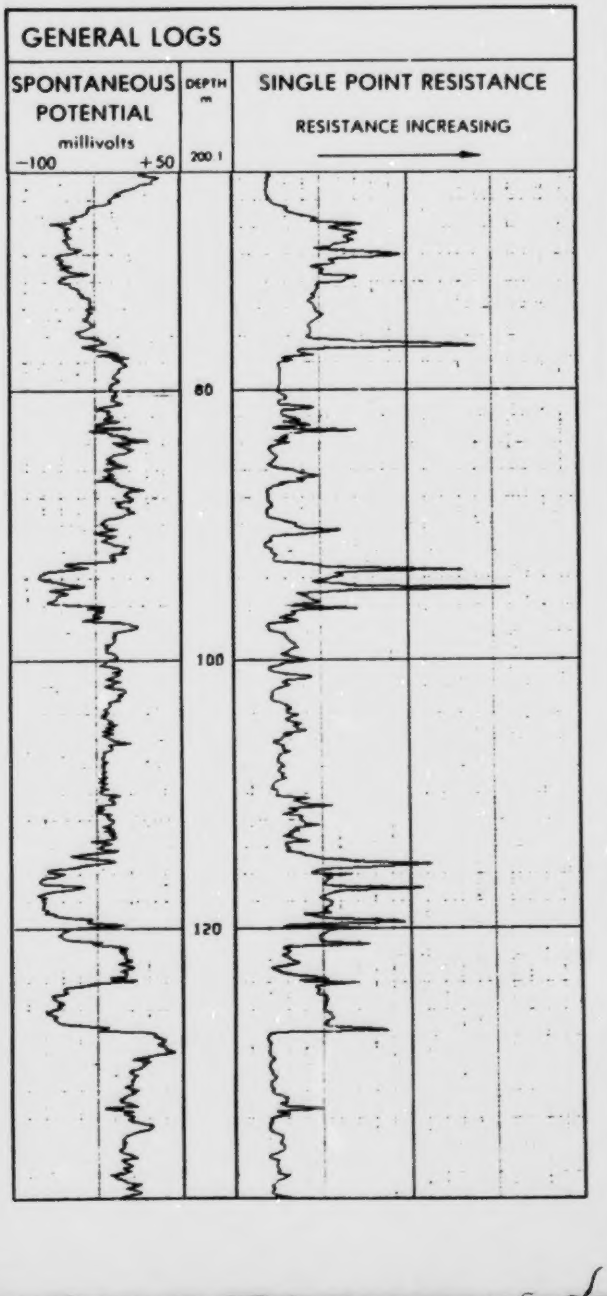
The Resistance (Res) log is a record of the resistance of the formations between a downhole electrode and a surface fish. It is a useful qualitative log with high vertical resolution and shallow depth of investigation.

PRESENTATION:

Logs may be recorded in metric or imperial units of depth and are available for presentation with full flexibility of vertical and horizontal scales.

The Spontaneous Potential measurement is presented on a millivolts scale with reference to the ground electrode.

The Resistance log is presented as an uncalibrated indicator of formation resistivities.



APPLICATION SUMMARY:

The SP log is used for geological correlation, bed thickness determination and to differentiate between porous and non porous rocks in sandstone-shale and carbonate-shale sequences. Streaming potentials associated with zones gaining or losing water are sometimes detected.

The Resistance log is very useful for lithology correlation and as a fluid level and casing shoe indicator, with high vertical resolution for the determination of bed thickness. The RO1 Focussed Electric Sonde should, however, be selected whenever quantitative resistivity measurements are required, see Subsurface leaflet No. 4.

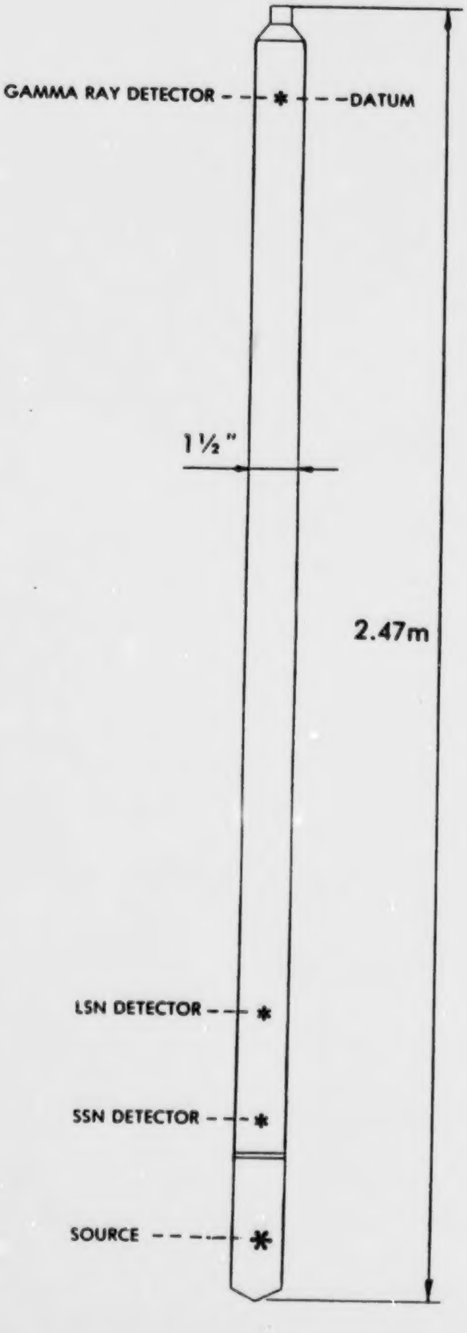
NN1 DUAL NEUTRON, GAMMA RAY, SONDE.

(OR DSN)

MEASUREMENTS:

RATIO NEUTRON POROSITY
SHORT SPACING NEUTRON (SSN)
LONG SPACING NEUTRON (LSN)
GAMMA RAY

The NN1 Sonde provides dual spacing Neutron (as also available from separate runs of the NO1 Sonde), Neutron Porosity and Gamma Ray logging in a single package. Furthermore, the Ratio based porosity measurement provides a degree of compensation, linearity and caliper independency not possible from a single detector system.



GENERAL SPECIFICATIONS:

Length — 2.47 m (8.10')
Weight — 14 kg (30 lbs)
Diameter — 3.8 cm (1½")
Temperature — up to 70°C (158°F)
Pressure — up to 210 kg/cm² (3000 p.s.i.)

OPERATING CONDITIONS:

Hole Depth — to a max. of approx.: 2000 m (6500')
Hole Diameter — open hole: 6.0 to 30 cm (2.5" to 12")
casing or rods: 5.0 to 30 cm (2.0" to 12")

Logging Speed — standardly: 9m/min (30'/min)
detail logging: 2.25m/min (7.5'/min)
Logging Mode — free running

Optimum calibration of Neutron Porosity, based in the NN1 system on the ratio of Long and Short spacing logs, requires open fluid filled holes in reasonable condition. Valuable, although more qualitative logging will continue to be feasible in dry holes, through casing or drill rods and at increased diameters.

TECHNICAL INFORMATION:

The Neutron Log is, in a fluid filled borehole, a measure of the ability of the formation to absorb thermal neutrons. This ability is a function of hydrogen in the formation and, therefore, after correction for borehole effects, the Neutron Log may be presented as an Index of Hydrogen and/or in turn as a measurement of formation porosity. High energy neutrons are emitted through 360° around the logging source. In a fluid filled hole these fast neutrons are slowed down (or thermalised) in a region very close to the source. In an air filled hole thermalisation and absorption both take place in the formation.

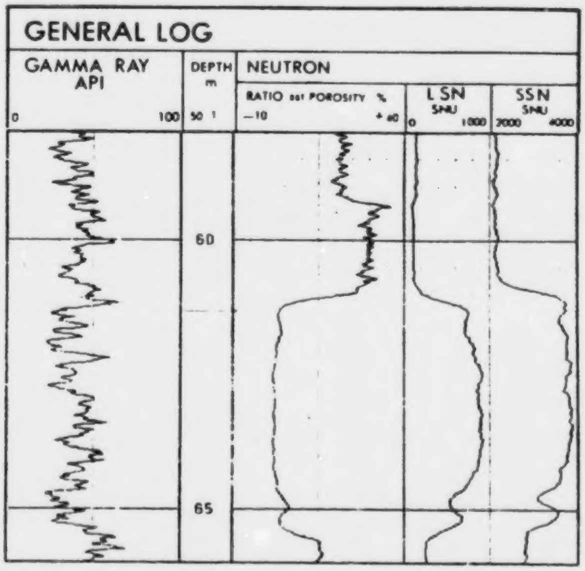
Both Neutron Detectors are uncollimated Helium$_3$ Tubes and are spaced 45 cms (Long Spacing) and 25 cms (Short Spacing) from the logging source. Calibration uses portable passive jigs to allow log presentation in calibrated units for all three outputs. The LSN and SSN are available as individual logs if required, although the Ratio Log provides the definitive porosity measurement.

SOURCE — a double encapsulated sealed source of Americium 241/Beryllium at an activity of One Curie is mounted in a stainless steel holder and locked securely to the sonde during logging operations. The source holder is transported in a purpose designed shield with a maximum surface radiation level of 2 mR/hr (gamma) and 6 mR/hr (Neutron).

The Gamma Ray system is identical to that described in the DD1 leaflet No. 1.

PRESENTATION:

A range of presentations of Ratio Porosity, SSN, LSN, and Gamma Ray logs are available with a full flexibility of format and vertical and horizontal scales.



APPLICATION SUMMARY:

RATIO	— Lithology Identification and Correlation and, in open fluid filled holes, Hydrogen Index/Porosity measurement for quantitative formation evaluation.
SSN	— Porosity indication plus high resolution Lithology Identification, Correlation and Bed Thickness evaluation; particularly useful in higher apparent porosity formations.
LSN	— Porosity indication plus Lithology Identification and Correlation.

Neutron logs are also being used, through empirically established relationships, for Strength and Fracture analysis of coal measure formations.

GAMMA RAY — Shale content, Lithology Identification and Correlation.

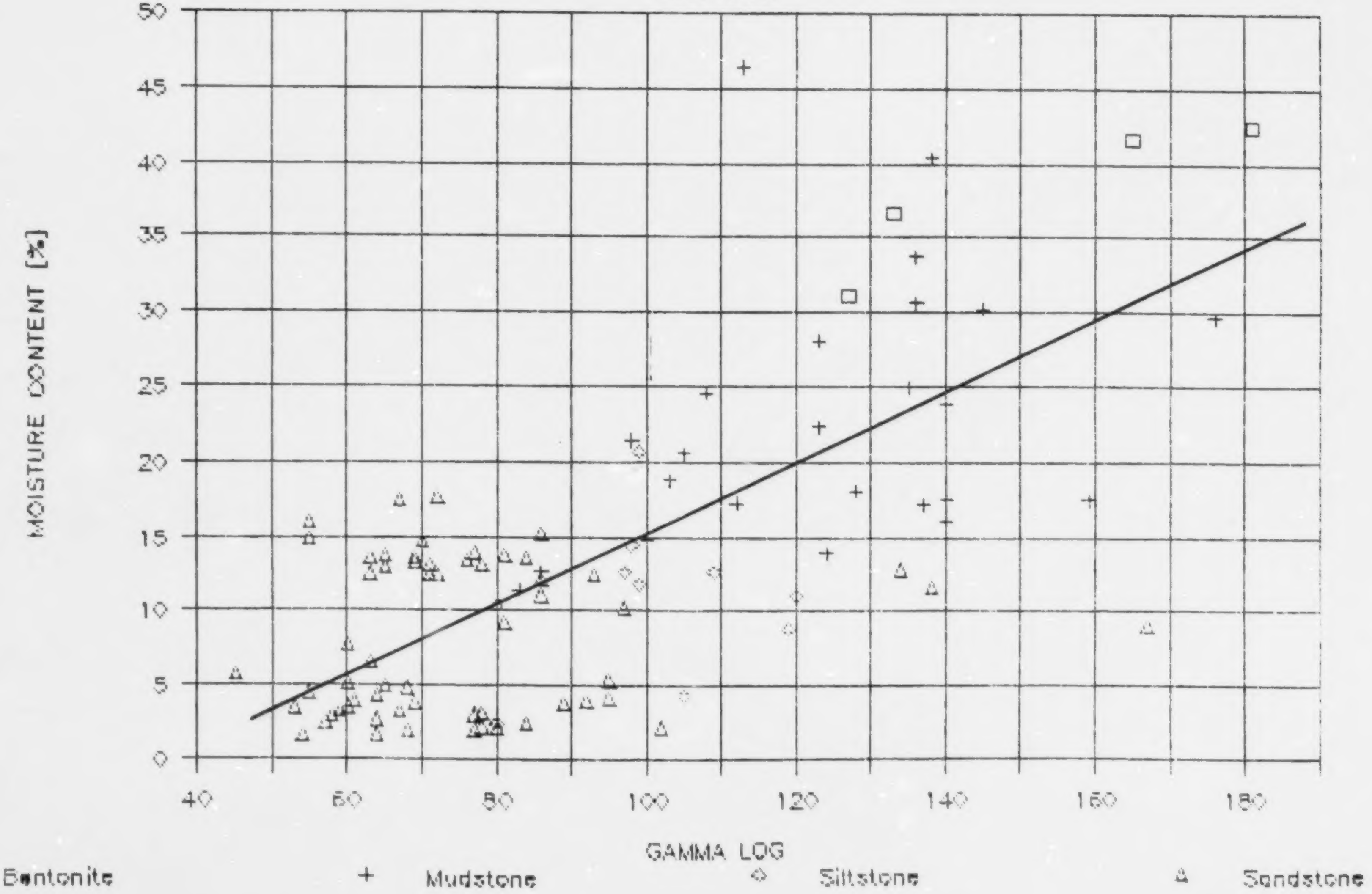
The NN1 Sonde is seen as a comprehensive porosity and lithology evaluation package, suited to the full range of slim hole environments. In addition its physical dimensions and the nature of its measurements make the NN1 particularly useful for qualitative logging in less than optimum conditions, e.g. through casing or drill rods, or in dry holes.

APPENDIX III

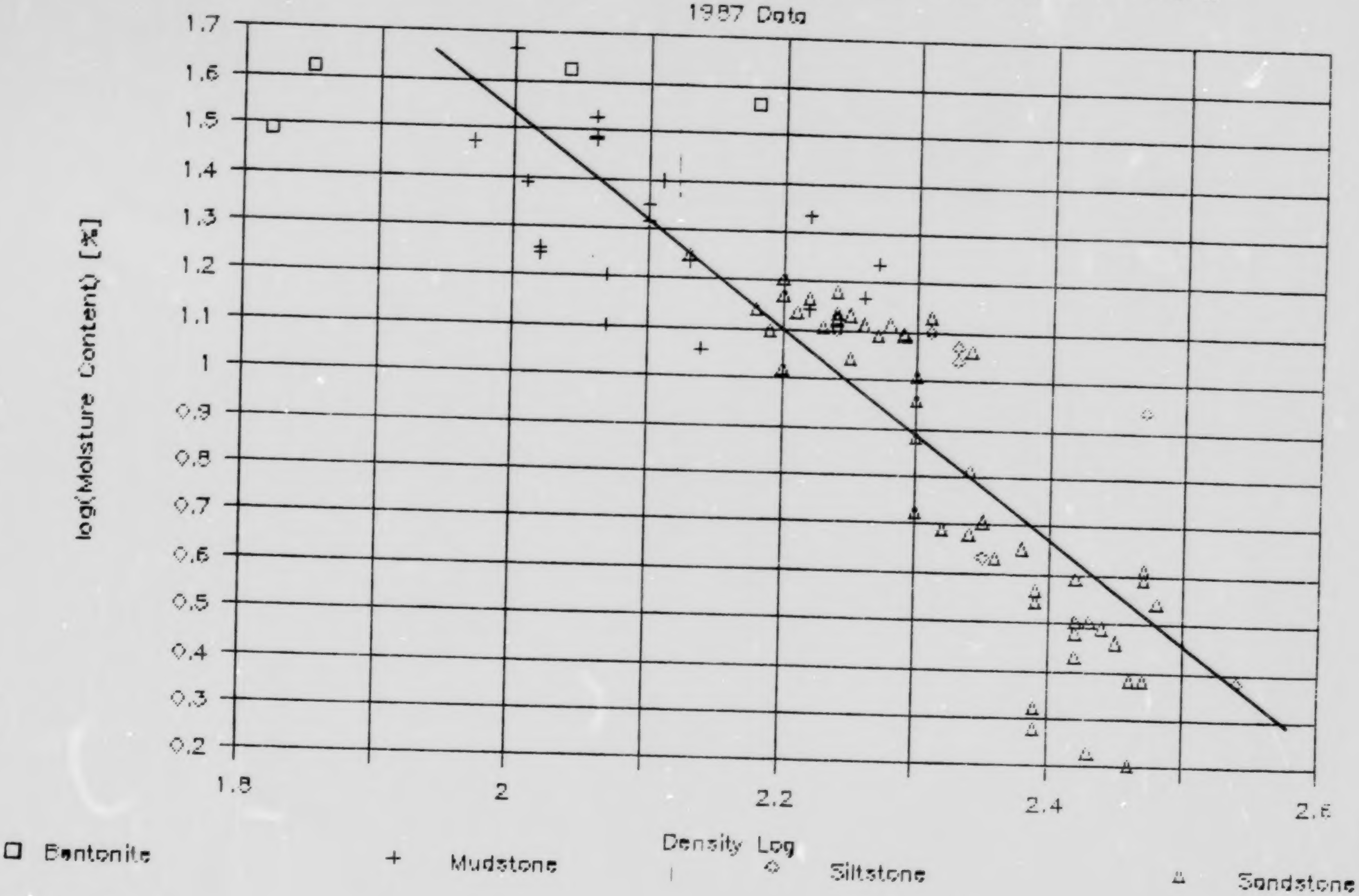
GEOTECHNICAL COAL CORRELATIONS

MOISTURE CONTENT vs GAMMA LOG

1987 Data

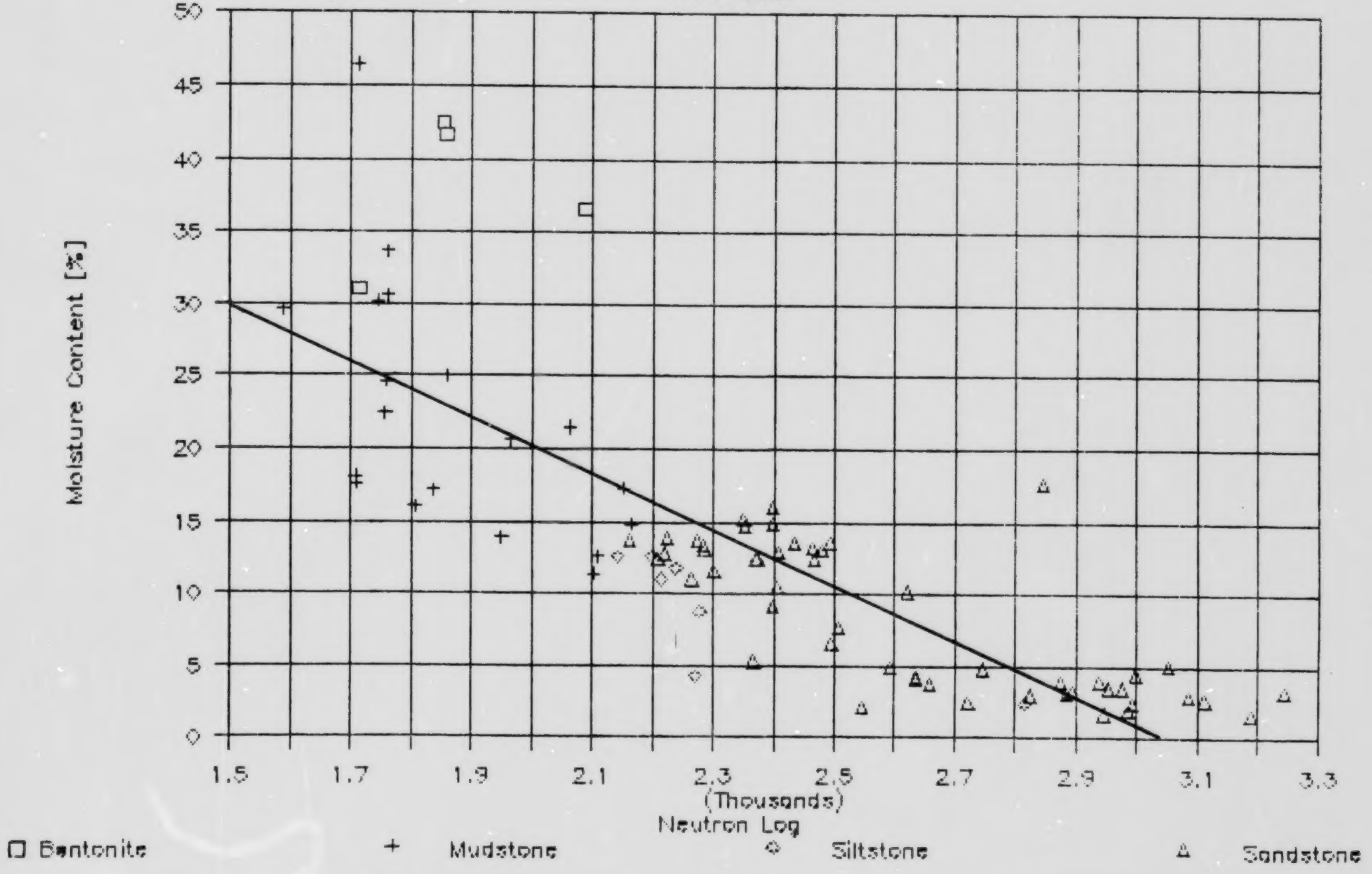


log(MOISTURE CONTENT) vs DENSITY LOG



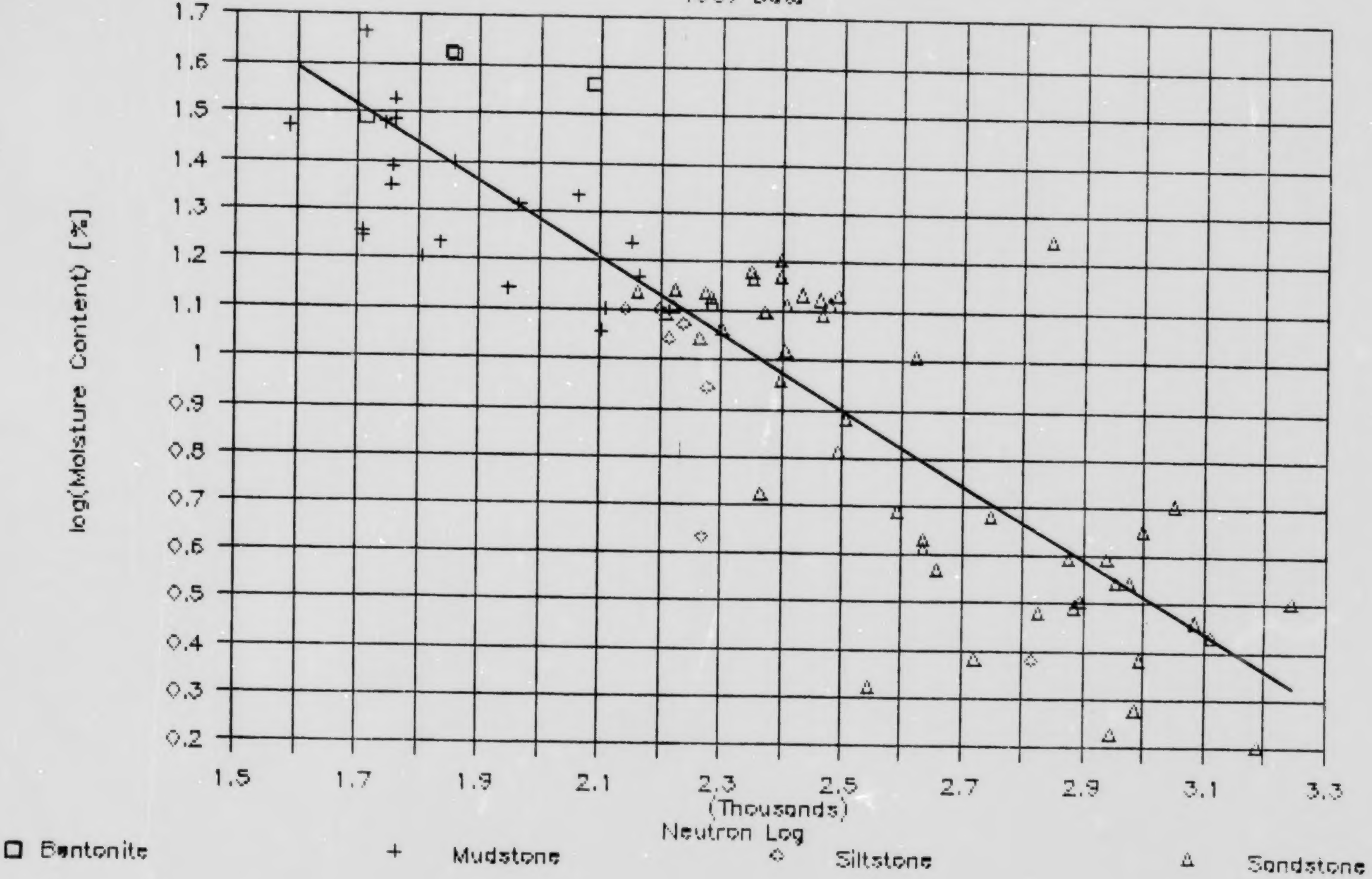
MOISTURE CONTENT vs NEUTRON LOG

1987 Data



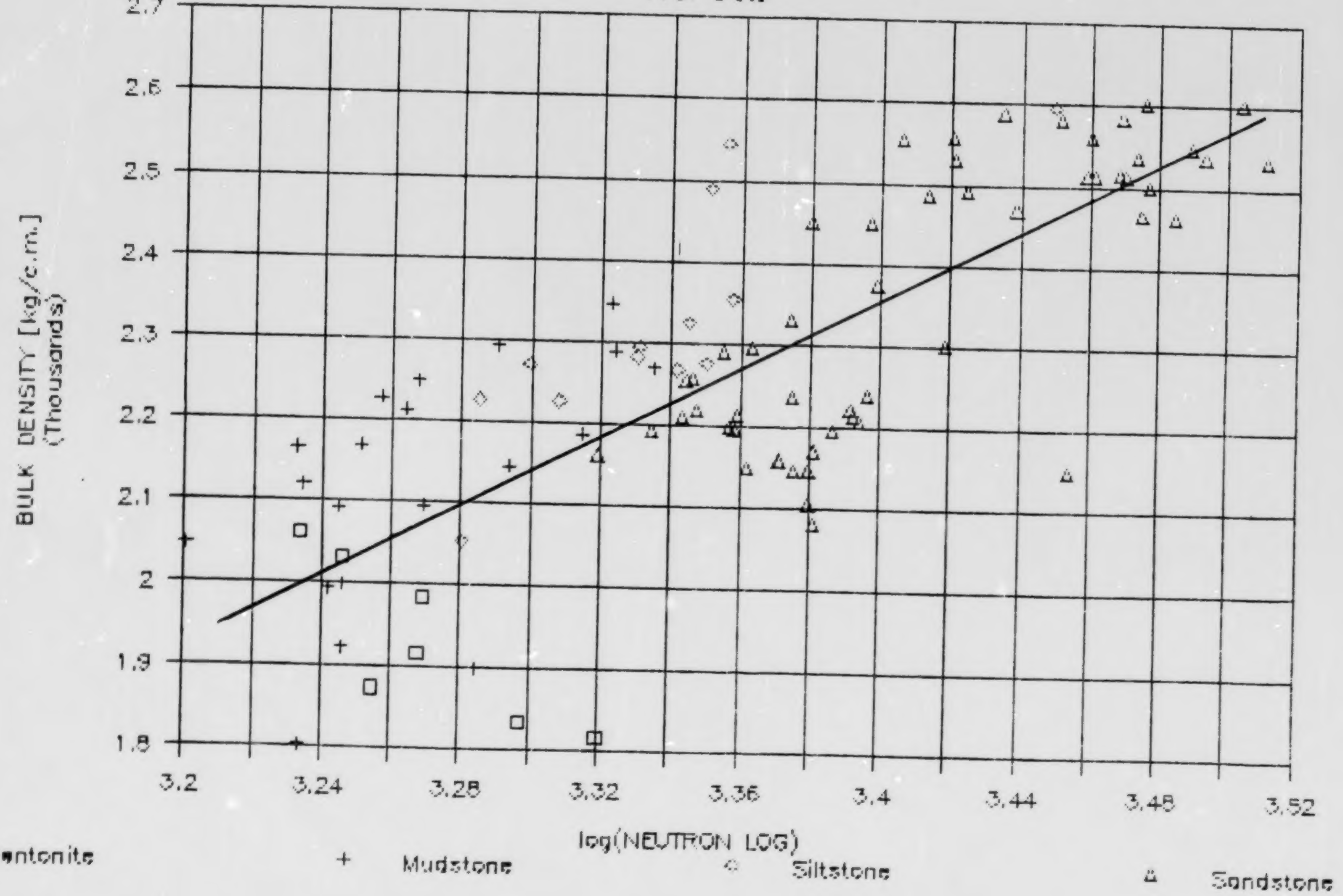
log(MOISTURE CONTENT) vs NEUTRON LOG

1987 Data



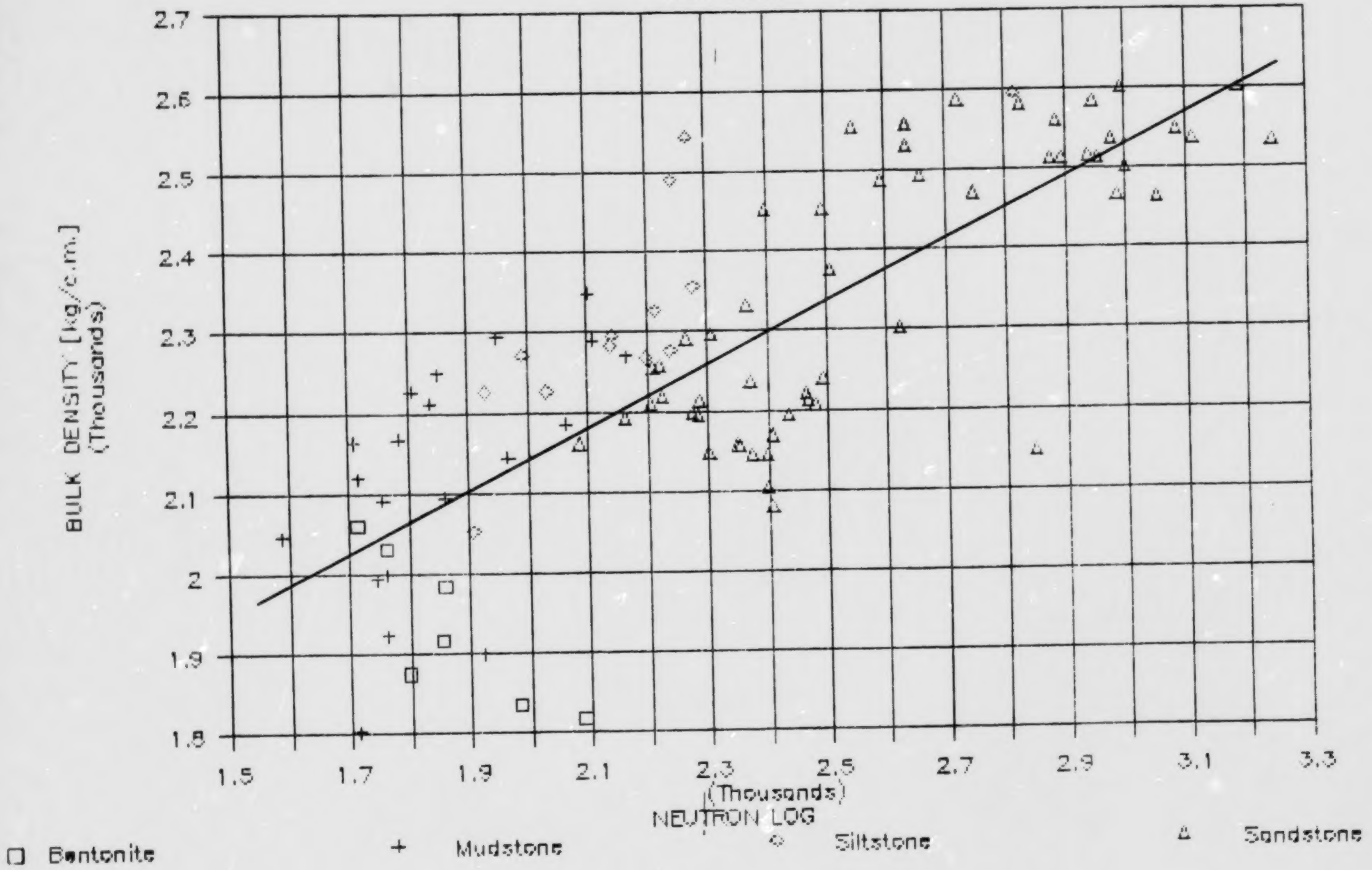
BULK DENSITY vs log(NEUTRON LOG)

1987 Data



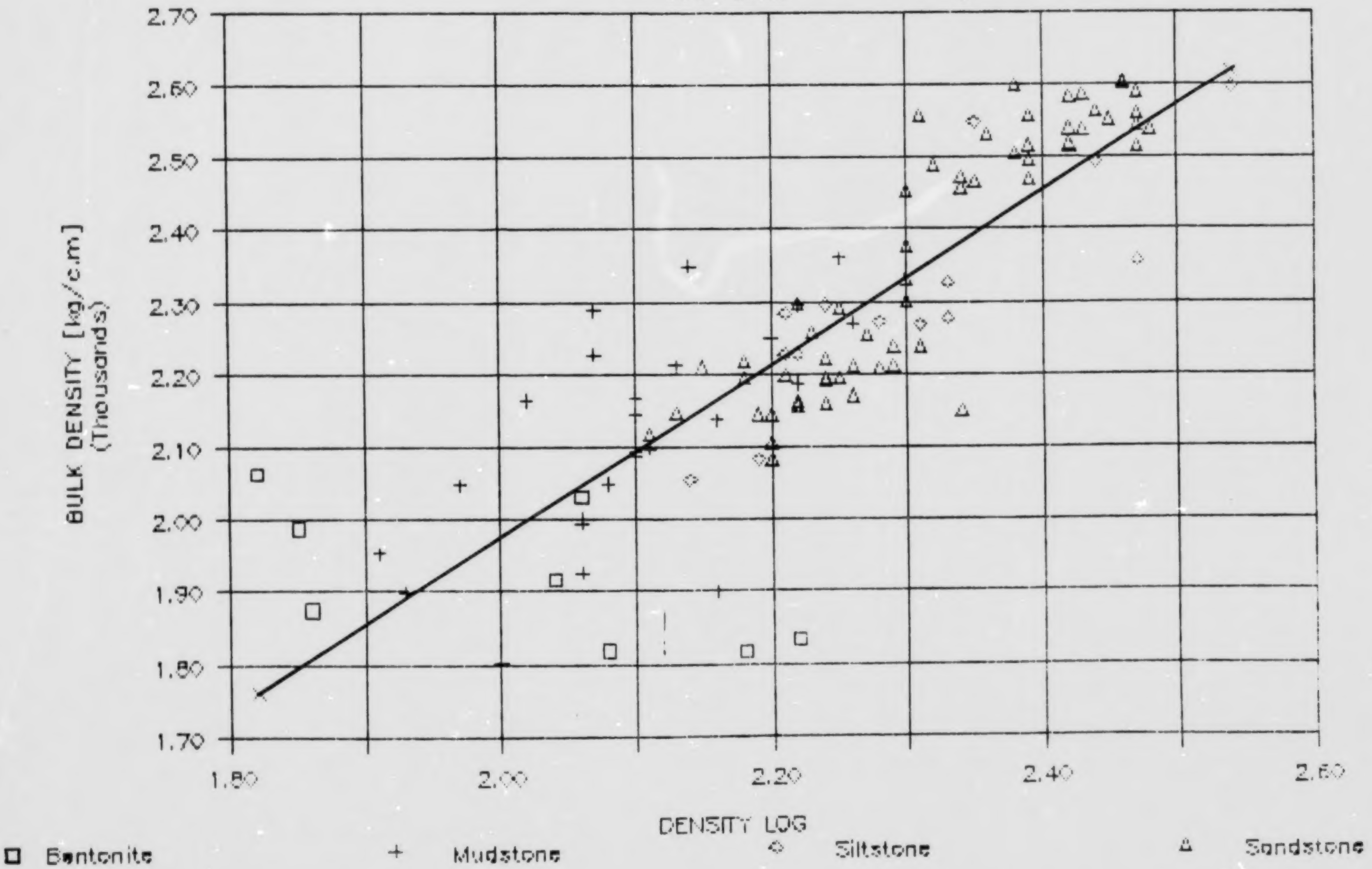
BULK DENSITY vs NEUTRON LOG

1987 Data



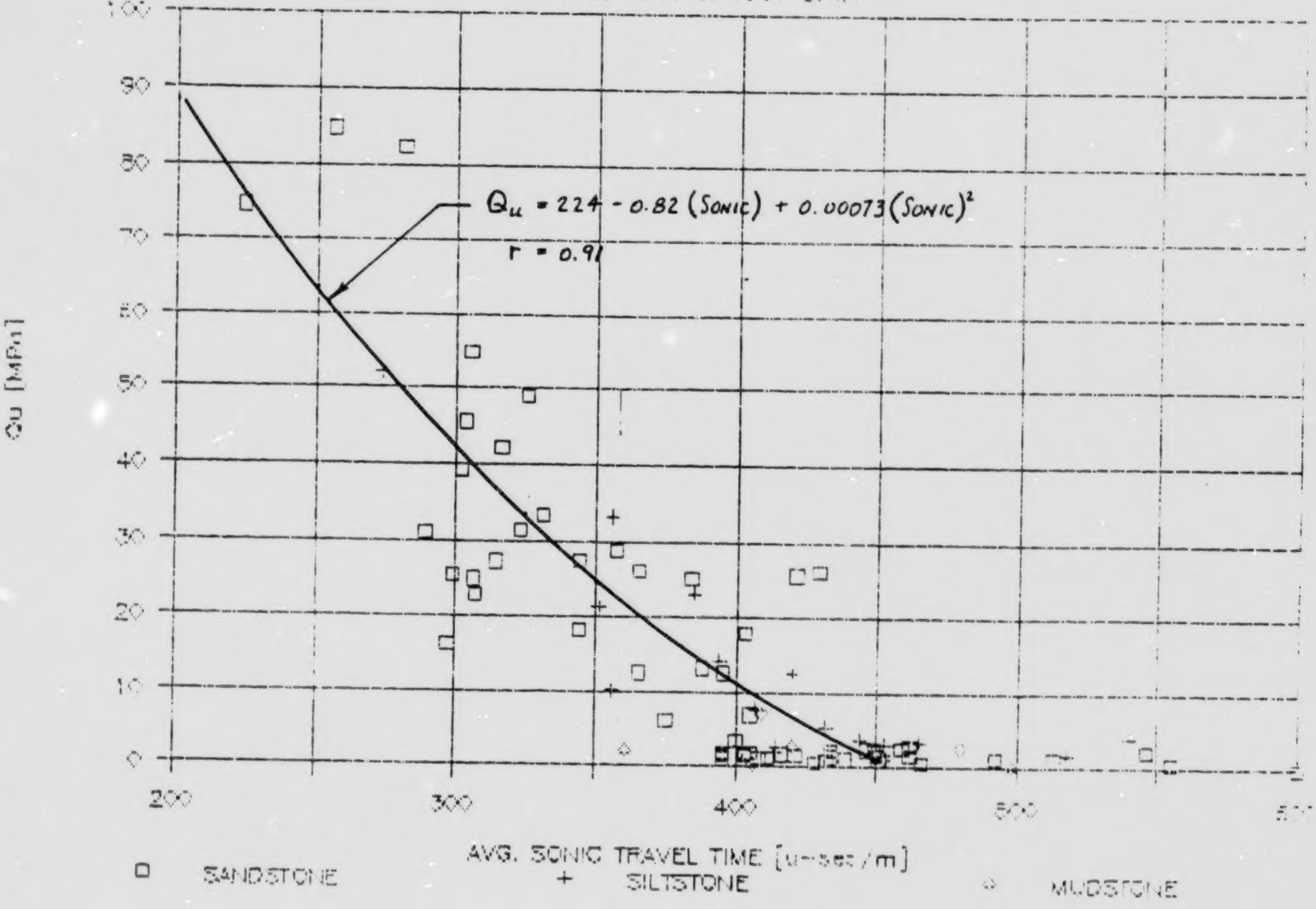
BULK DENSITY vs DENSITY LOG

1987 Data



Qu vs SONIC TRAVEL TIME

1982, 1983 & 1987 DATA

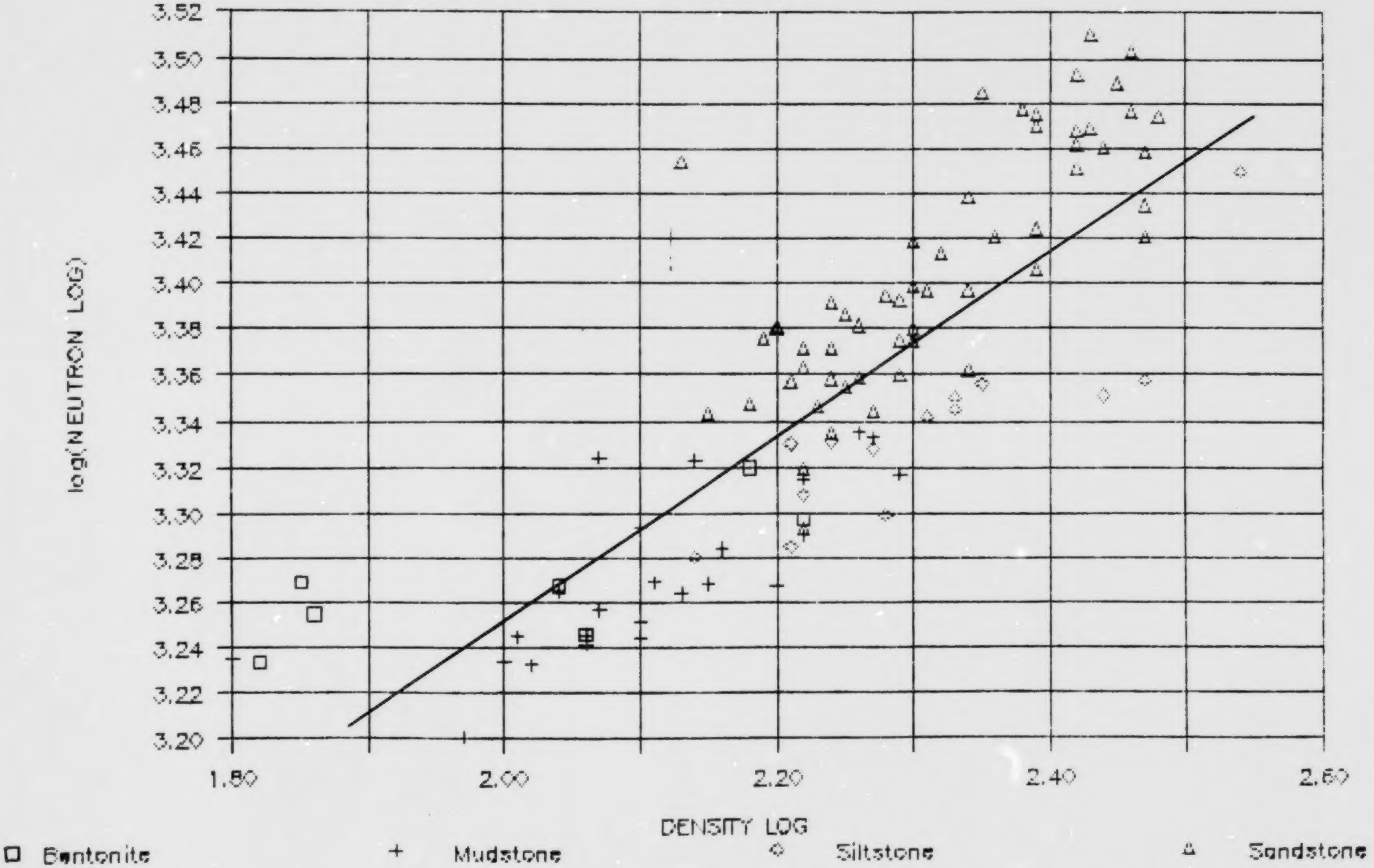


$Q_u = 224 - 0.82\,(Sonic) + 0.00073\,(Sonic)^2$

$r = 0.91$

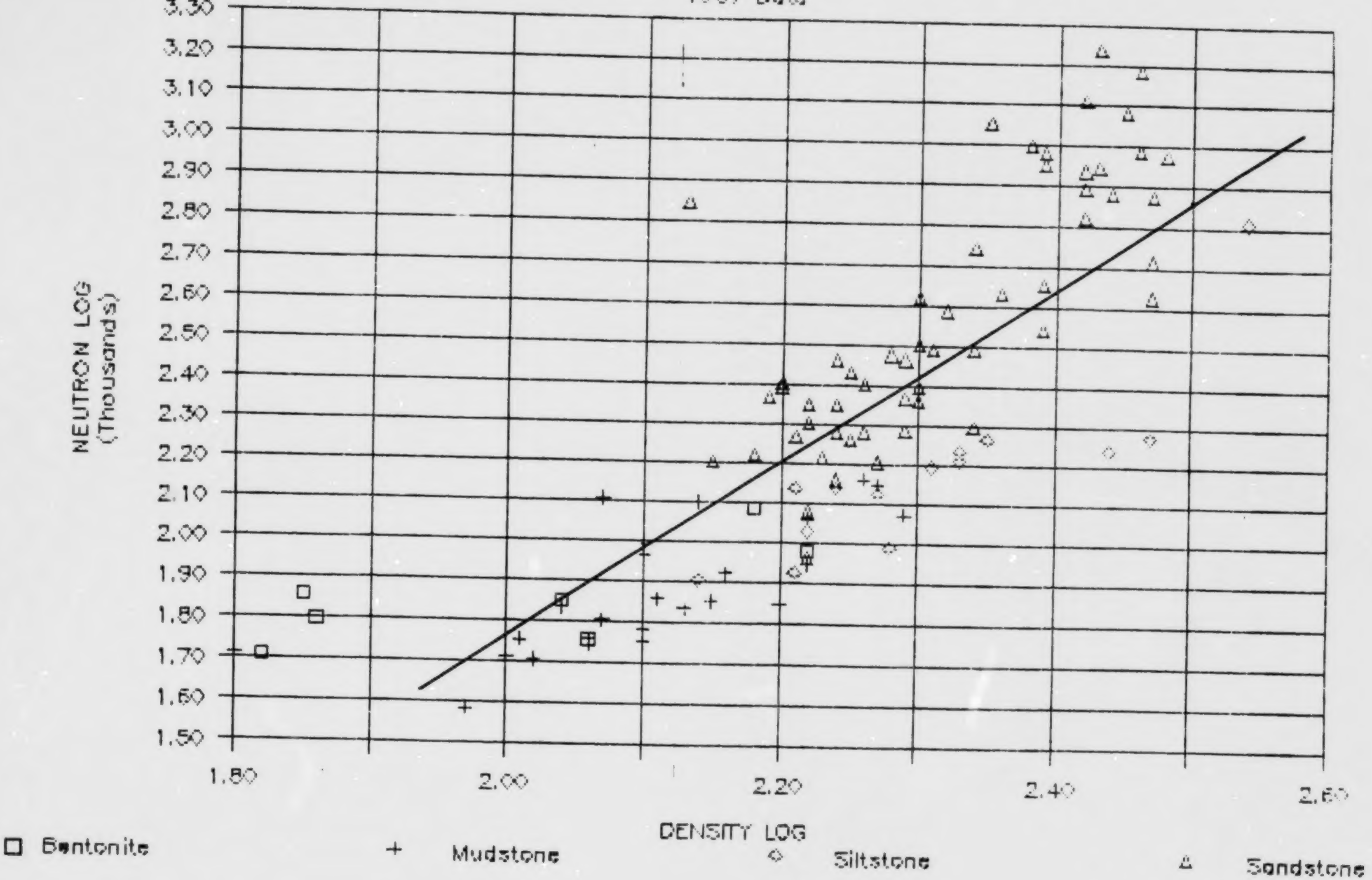
log(NEUTRON) vs DENSITY LOG

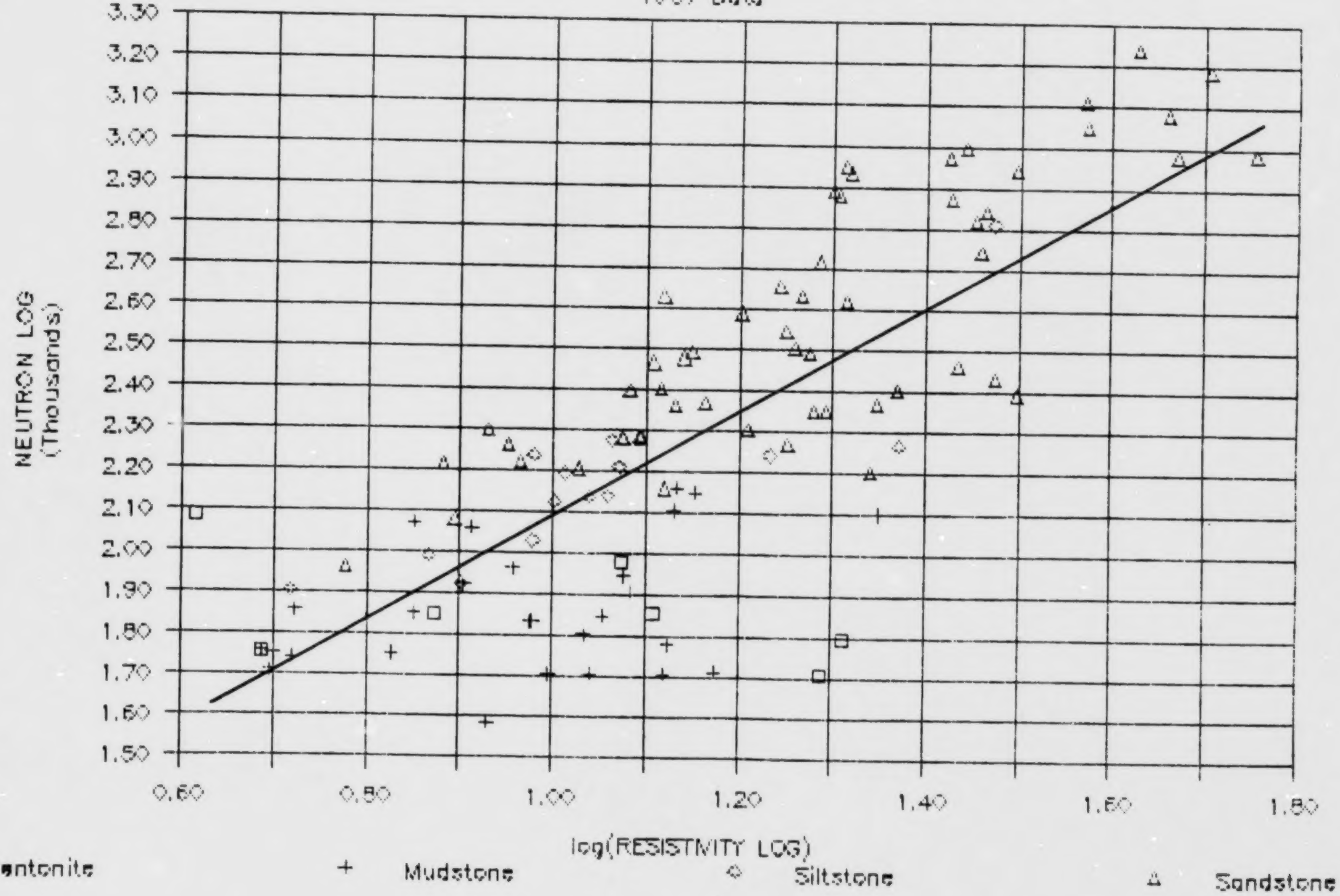
1987 Data



NEUTRON LOG vs DENSITY LOG

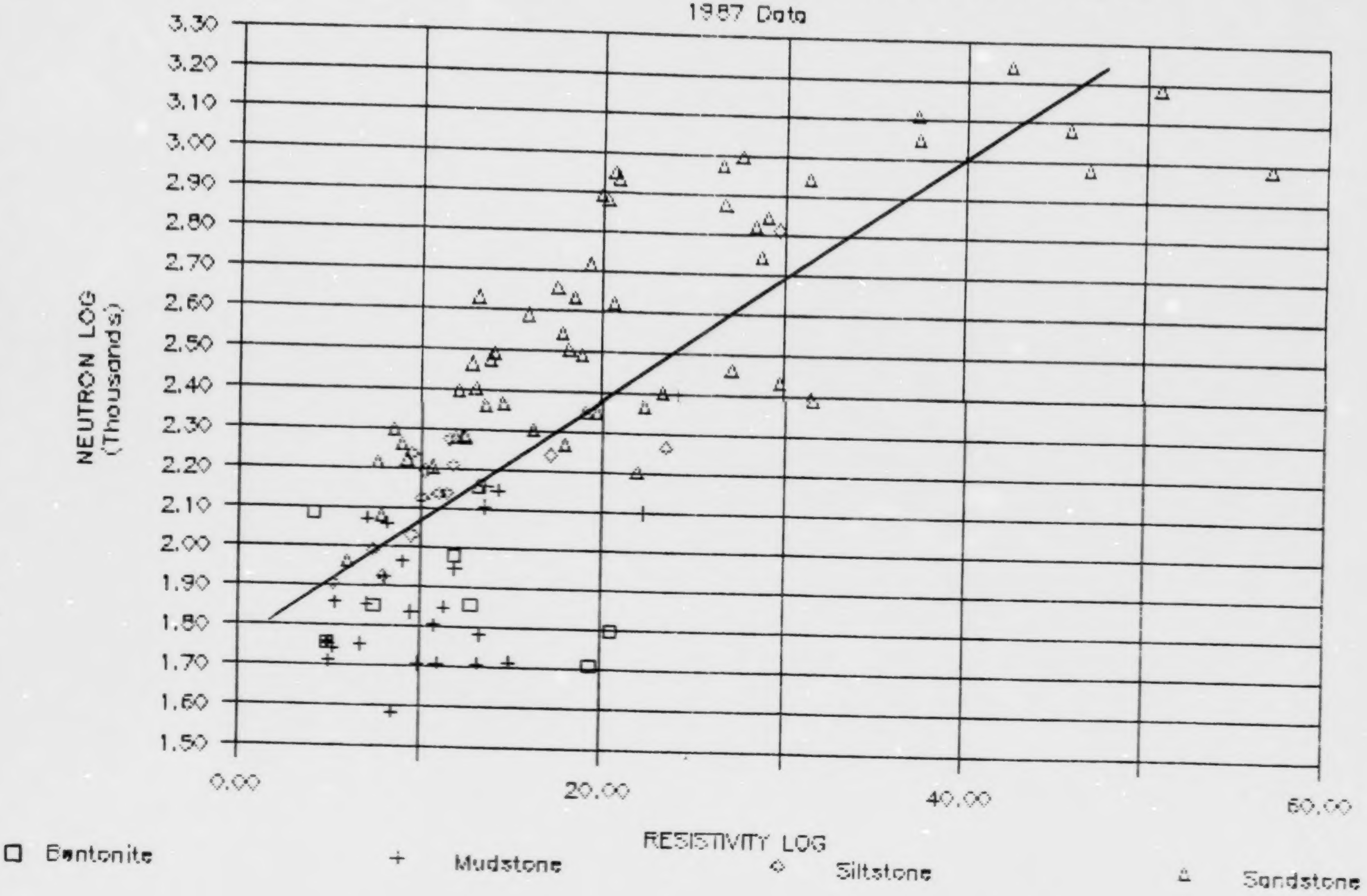
1987 Data





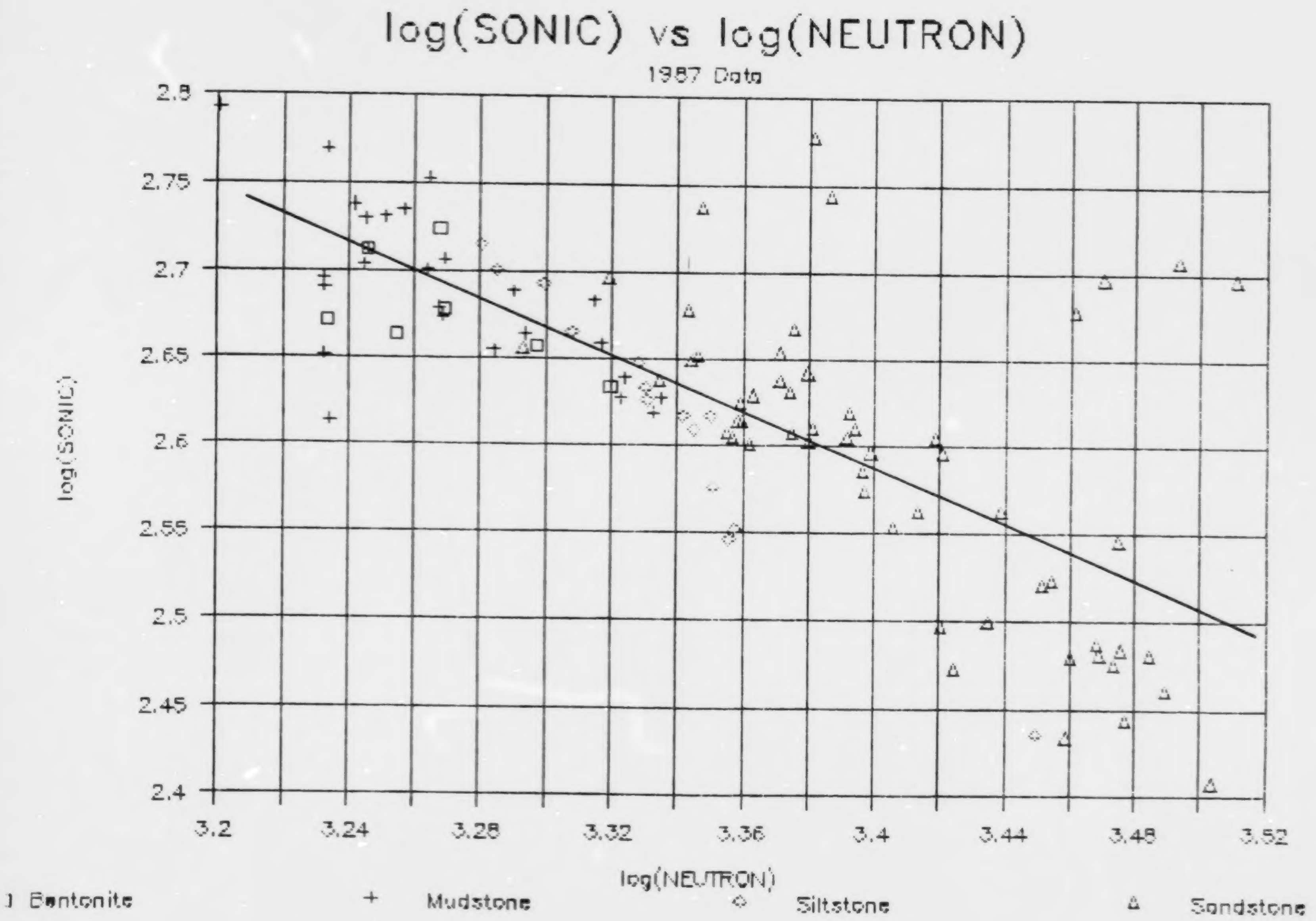
NEUTRON vs log(RESISTIVITY)

1987 Data



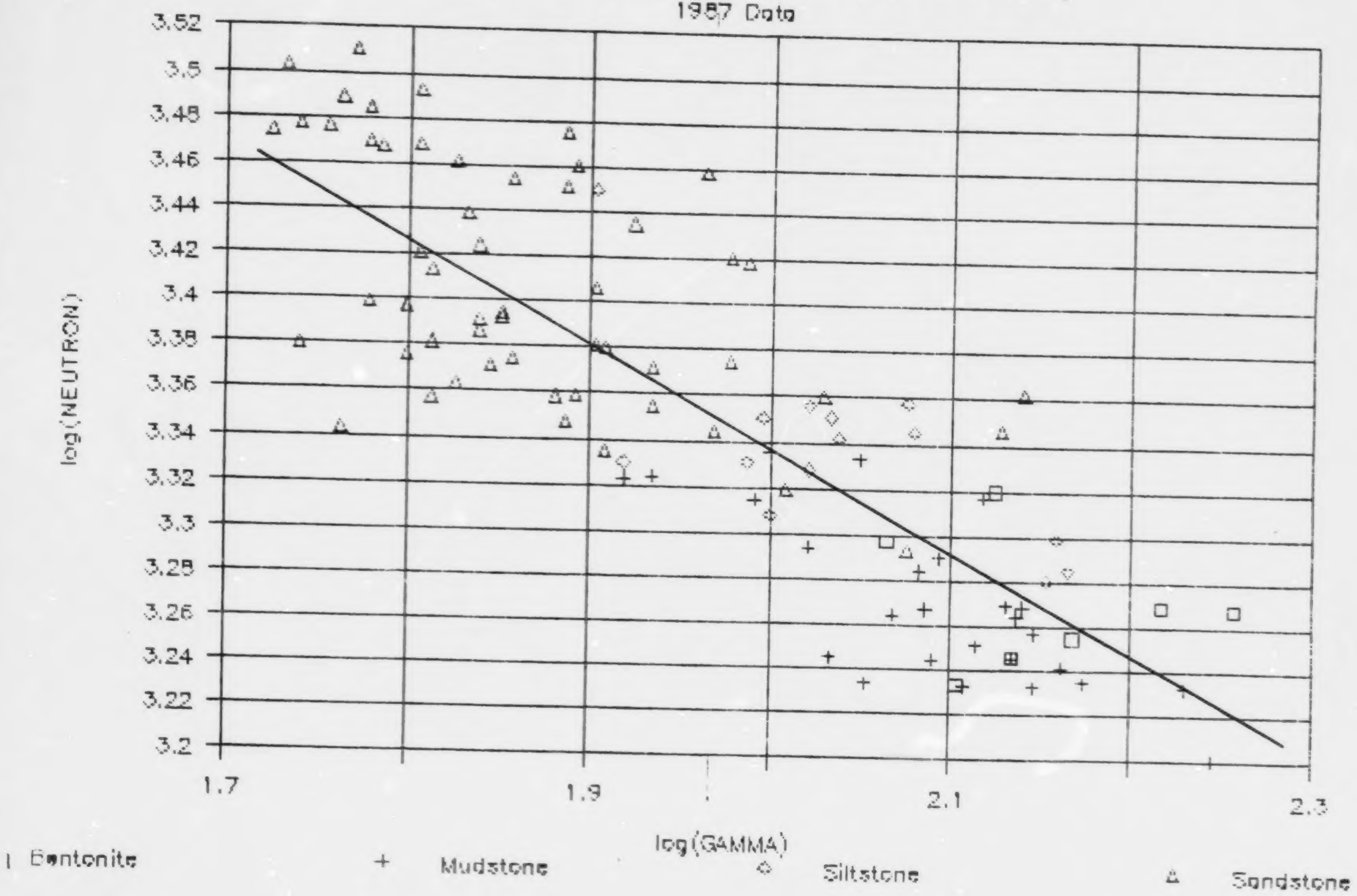
NEUTRON LOG vs RESISTIVITY LOG

1987 Data


log(SONIC) vs log(NEUTRON)
1987 Data
log(SONIC)
2.8
2.75
2.7
2.65
2.6
2.55
2.5
2.45
2.4
log(NEUTRON)
3.2
3.24
3.28
3.32
3.36
3.4
3.44
3.48
3.52
] Bentonite
+ Mudstone
◇ Siltstone
△ Sandstone

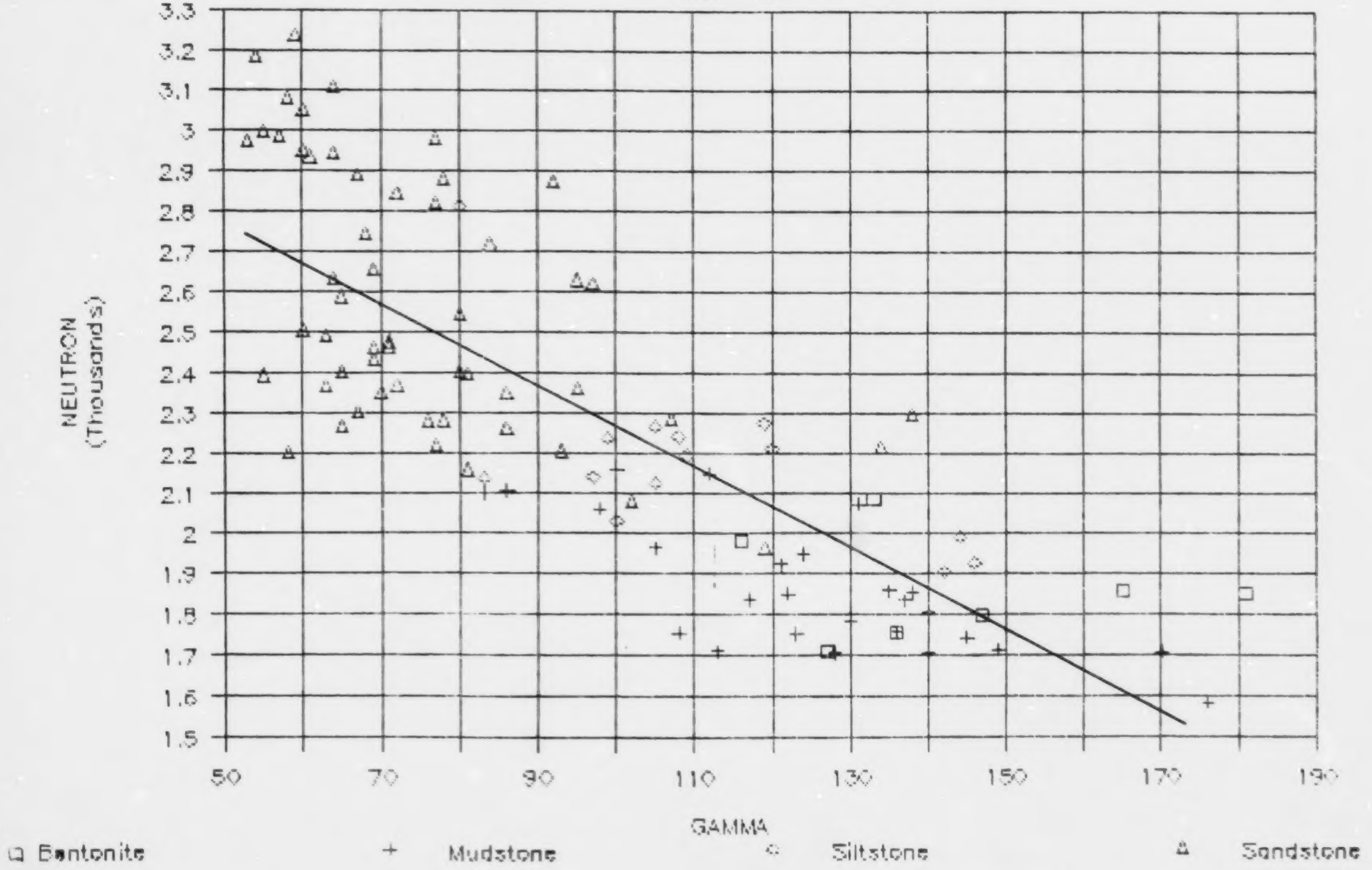
log(NEUTRON) vs log(GAMMA)

1987 Data



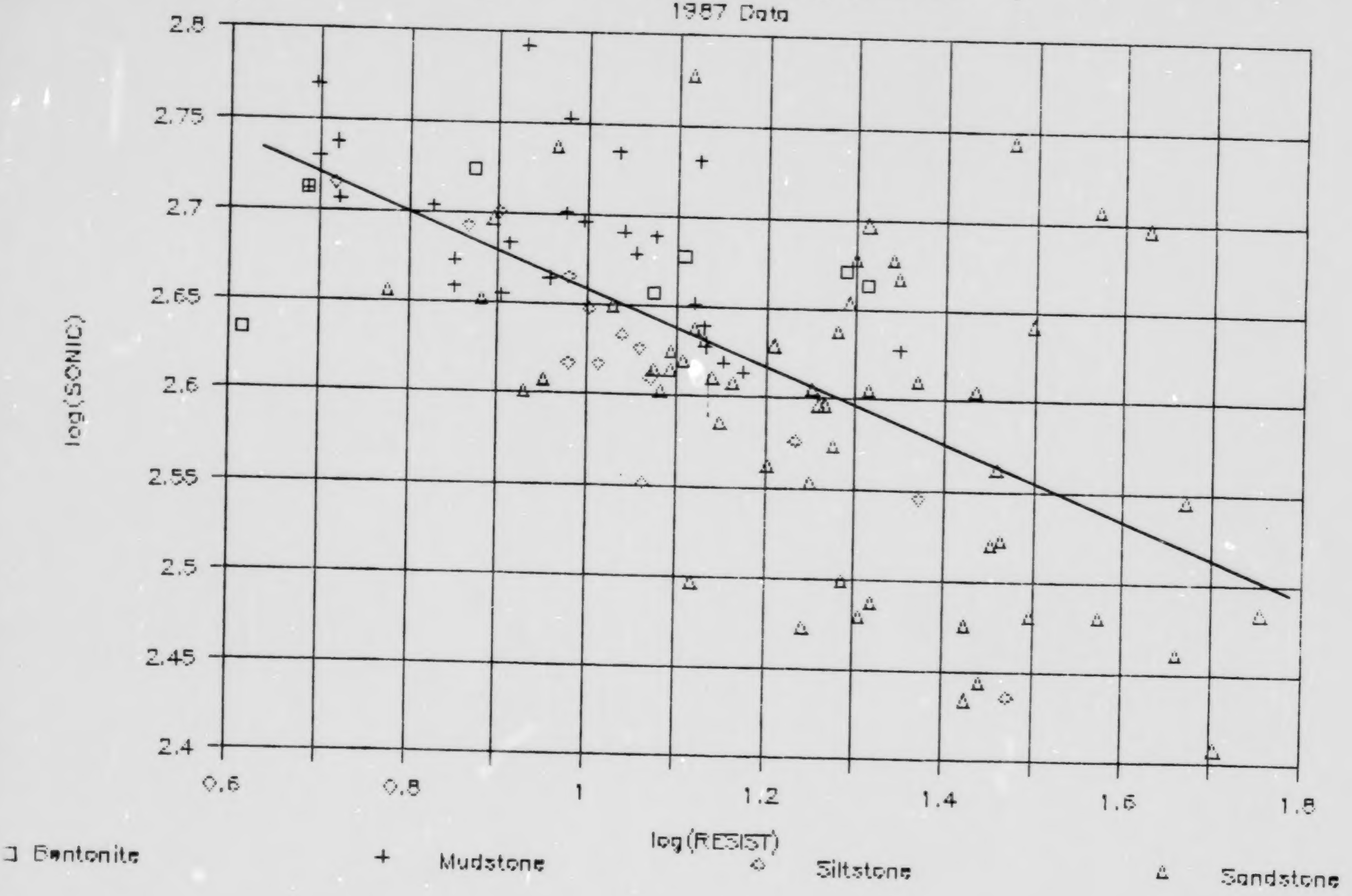
NEUTRON vs GAMMA

1987 Data



log(SONIC) vs log(RESIST)

1987 Data



```
BV25:                                                                   READY

        BH        BI        BJ        BK        BL        BT        BU        BV
 7             log(NEUT) vs log(GAMMA)
 8             Regression Output:
 9   Constant                          4.236617
10   Std Err of Y Est                  0.043187
11   R Squared                         0.697256 R=0.835
12   No. of Observations                    105
13   Degrees of Freedom                     103
14
15   X Coefficient(s)   -0.44942
16   Std Err of Coef.   0.029179
17
18
19             SONIC vs RESISTIVITY
20             Regression Output:
21   Constant                          501.3026
22   Std Err of Y Est                  65.54834
23   R Squared                         0.313358 R=0.560
24   No. of Observations                    105
25   Degrees of Freedom                     103
23-Mar-88  08:49 PM

BV45:                                                                   READY

        BH        BI        BJ        BK        BL        BT        BU        BV
26
27   X Coefficient(s)   -4.17499
28   Std Err of Coef.   0.608950
29
30
31             log(SONIC) vs log(RESIST)
32             Regression Output:
33   Constant                          2.858871
34   Std Err of Y Est                  0.066186
35   R Squared                         0.380009 R=0.616
36   No. of Observations                    105
37   Degrees of Freedom                     103
38
39   X Coefficient(s)   -0.20172
40   Std Err of Coef.   0.025388
41
42
43             SONIC vs NEUTRON
44             Regression Output:
45   Constant                          738.6543
23-Mar-88  08:50 PM

BV65:                                                                   READY

        BH        BI        BJ        BK        BL        BT        BU        BV
46   Std Err of Y Est                  55.65467
47   R Squared                         0.504994 R=0.711
48   No. of Observations                    105
49   Degrees of Freedom                     103
```

```
 54
 55            log(SONIC) vs log(NEUTRON)
 56            Regression Output:
 57  Constant                          5.250330
 58  Std Err of Y Est                  0.057382
     R Squared                         0.533972 R=0.731
     No. of Observations                    105
 61  Degrees of Freedom                     103
 62
 63  X Coefficient(s)   -0.78255
 64  Std Err of Coef.    0.072034
 65
23-Mar-88  08:50 PM

BV85:
                                                                READY


        BH       BI       BJ       BK       BL       BT       BU       BV
 66
 67            SONIC vs log(NEUTRON)
 68            Regression Output:
 69  Constant                          2861.474
 70  Std Err of Y Est                  54.94919
 71  R Squared                         0.517464 R=0.719
 72  No. of Observations                    105
 73  Degrees of Freedom                     103
 74
 75  X Coefficient(s)   -724.963
 76  Std Err of Coef.   68.97978
 77
 78
               log(SONIC) vs NEUTRON
 80            Regression Output:
 81  Constant                          2.961924
 82  Std Err of Y Est                  0.057580
 83  R Squared                         0.530756 R=0.729
 84  No. of Observations                    105
 85  Degrees of Freedom                     103
23-Mar-88  08:50 PM

BV105:
                                                                READY


        BH       BI       BJ       BK       BL       BT       BU       BV
 86
 87  X Coefficient(s)   -0.00014
 88  Std Err of Coef.    0.000013
 89
 90
 91
 92
 93
 94
 95
 96
 97
 98

101
 02
 03
```

```
:D24:                                                                        READY

        AZ        BA        BB        BC        BD        CD        CE        CF
 5
                log(Neutron) vs log(Resist)
                Regression Output:
 8  Constant                        3.079926
 9  Std Err of Y Est                0.049580
10  R Squared                       0.600995 R=0.775
 1  No. of Observations                  105
12  Degrees of Freedom                   103
13
.4  X Coefficient(s)   0.236891
.5  Std Err of Coef.   0.019018
16
.7
.8              log(Neut/St) vs log(Resist)
19              Regression Output:
20  Constant                        1.057950
21  Std Err of Y Est                0.045882
22  R Squared                       0.534783 R=0.73
23  No. of Observations                  105
24  Degrees of Freedom                   103
3-Mar-88  08:52 PM

:D44:                                                                        READY

        AZ        BA        BB        BC        BD        CD        CE        CF
25
    X Coefficient(s)   0.191514
27  Std Err of Coef.   0.017600
28
29
30              log(Neut/Res) vs log(Sonic)
31              Regression Output:
32  Constant                        -9.00345
33  Std Err of Y Est                0.587210
34  R Squared                       0.301950 R=0.55
35  No. of Observations                  105
36  Degrees of Freedom                   103
37
38  X Coefficient(s)   4.594533
39  Std Err of Coef.   0.688332
40
41
42              SONIC vs GAMMA
43              Regression Output:
44  Constant                        305.7907
3-Mar-88  08:52 PM

CD64:                                                                        READY

        AZ        BA        BB        BC        BD        CD        CE        CF
45  Std Err of Y Est                66.84024
    R Squared                       0.286025 R=0.535
    No. of Observations                  105
48  Degrees of Freedom                   103
 9
 0  X Coefficient(s)   1.278727
 54            SONIC vs NEUT/GAMMA
 55            Regression Output:
 56  Constant                            530.6613
 57  Std Err of Y Est                    63.13370
 58  R Squared                           0.363015 R=0.603
 59  No. of Observations                      105
 60  Degrees of Freedom                       103

 62  X Coefficient(s)   -3.64886
 63  Std Err of Coef.   0.476257
 64
23-Mar-88  08:52 PM

CD84:
                                                                          READY

         AZ         BA         BB         BC         BD         CD         CE         CF
 65
 66            SONIC vs log[NEUT/GAMMA]
 67            Regression Output:
 68  Constant                            746.4099
 69  Std Err of Y Est                    62.00604
 70  R Squared                           0.385566 R=0.621
 71  No. of Observations                      105
 72  Degrees of Freedom                       103
 73
 74  X Coefficient(s)   -227.670
 75  Std Err of Coef.   28.31888
 76
 77
 78            SONIC vs NEUT*GAMMA
 79            Regression Output:
     Constant                            341.4951
 81  Std Err of Y Est                    76.82715
 82  R Squared                           0.056729 R=0.238
 83  No. of Observations                      105
 84  Degrees of Freedom                       103
23-Mar-88  08:53 PM

CD104:
                                                                          READY

         AZ         BA         BB         BC         BD         CD         CE         CF
 85
 86  X Coefficient(s)   0.000421
 87  Std Err of Coef.   0.000169
 88
 89
 90            SONIC vs NEUT*RESIST/GAMMA
 91            Regression Output:
 92  Constant                            471.0086
 93  Std Err of Y Est                    66.31210
 94  R Squared                           0.297264 R=0.545
 95  No. of Observations                      105
 96  Degrees of Freedom                       103
 97
 98  X Coefficient(s)   -0.07017
 99  Std Err of Coef.   0.010631


102            NEUTRON vs GAMMA
103            Regression Output:
104  Constant                            3284.468
23-Mar-88  08:53 PM
```

```
         AZ          BA          BB          BC          BD          CD          CE          CF
105 Std Err of Y Est                       248.4082
106 R Squared                              0.647110 R=0.804
107 No. of Observations                         105
  8 Degrees of Freedom                          103

110 X Coefficient(s)  -10.1675
111 Std Err of Coef.  0.739820
112
 13
114            log(NEUTRON) vs GAMMA
115            Regression Output:
 16 Constant                               3.544292
 17 Std Err of Y Est                       0.044354
118 R Squared                              0.680671 R=0.825
 19 No. of Observations                         105
 20 Degrees of Freedom                          103
121
122 X Coefficient(s)  -0.00195
 23 Std Err of Coef.  0.000132
124
23-Mar-88  09:03 PM

X32:                                                                                        READY
```

```
         AO          AP          AQ          AR          AS          BX          BY          BZ
13
14             Neut/Gam vs DENLOG
 5             Regression Output:
    Constant                             -98.4153
1   Std Err of Y Est _                   9.532734
 8  R Squared                            0.467361   R=0.68
 9  No. of Observations                       105
20  Degrees of Freedom                        103
 1
 2  X Coefficient(s)  56.20578
23  Std Err of Coef.  5.912247
24
 5
26             log(Neut/Gam) vs DENLOG
27             Regression Output:
 8  Constant                             -0.83734
 9  Std Err of Y Est                     0.147033
30  R Squared                            0.535531   R=0.73
 1  No. of Observations                       105
 2  Degrees of Freedom                        103
23-Mar-88  09:05 PM

X52:                                                                                        READY
```

```
         AO          AP          AQ          AR          AS          BX          BY          BZ
 3
34  X Coefficient(s)  0.993769
35  Std Err of Coef.  0.091191

               log(Neut/Gam) vs log(DENLOG)
38             Regression Output:
 9  Constant                             -0.34305
 0  Std Err of Y Est                     0.147682
 45  X Coefficient(s)   4.959617
 46  Std Err of Coef.   0.458876
 47
 48
 49           Neut*Gam vs DENLOG
 50           Regression Output:
     Constant                       404995.2
 52  Std Err of Y Est               42595.58
 23-Mar-88  09:05 PM

 BX72:
                                                                        READY

        AO        AP        AQ        AR        AS        BX        BY        BZ
 53  R Squared                      0.092473  R=0.30
 54  No. of Observations                 105
 55  Degrees of Freedom                  103
 56
 57  X Coefficient(s)  -85584.8
 58  Std Err of Coef.  26417.98
 59
 60
 61           GAMMA vs RESIST
 62           Regression Output:
 63  Constant                       131.3596
 64  Std Err of Y Est               25.60501
 65  R Squared                      0.401027  R=0.63
 66  No. of Observations                 105
 67  Degrees of Freedom                  103
 68
 69  X Coefficient(s)  -1.97536
     Std Err of Coef.  0.237872

 72
 23-Mar-88  09:05 PM

 BX92:
                                                                        READY

        AO        AP        AQ        AR        AS        BX        BY        BZ
 73           Neut*Gam/Resist vs DENLOG
 74           Regression Output:
 75  Constant                       103481.9
 76  Std Err of Y Est               12008.27
 77  R Squared                      0.200291  R=0.45
 78  No. of Observations                 105
 79  Degrees of Freedom                  103
 80
 81  X Coefficient(s)  -37826.7
 82  Std Err of Coef.  7447.588
 83
 4
 85           Neut*Res/Gam vs DENLOG
 86           Regression Output:
 7   Constant                       -4209.70
 88  Std Err of Y Est               512.3880
 89  R Squared                      0.304848 R=0.55
     No. of Observations                 105
     Degrees of Freedom                  103
 92
 23-Mar-88  09:05 PM

 BX1                                                                    READ
```

```
           AO          AP          AQ          AR          AS          BX          BY          BZ
 93  X Coefficient(s)  2135.774
 94  Std Err of Coef.  317.7855
 95
 96
 97            Neutron vs Resist
               Regression Output:
     Constant                      1769.041
100 Std Err of Y Est               260.3475
101 R Squared                      0.612373 R=0.78
102 No. of Observations                 105
103 Degrees of Freedom                  103
104
105 X Coefficient(s)  30.85270
106 Std Err of Coef.  2.418651
107
108
109           Neutron vs log(Resist)
110           Regression Output:
111 Constant                       813.3694
112 Std Err of Y Est               257.7537
23-Mar-88  09:06 PM

BX132:                                                                                   READY


           AO          AP          AQ          AR          AS          BX          BY          BZ
113 R Squared                      0.620058 R=0.79
114 No. of Observations                 105
115 Degrees of Freedom                  103
116
117 X Coefficient(s)  1281.906
    Std Err of Coef.  98.87344
119  _
120
121           log(Neutron) vs Resistivity
122           Regression Output:
123 Constant                       3.258456
124 Std Err of Y Est               0.051482
125 R Squared                      0.569790 R=0.75
126 No. of Observations                 105
127 Degrees of Freedom                  103
128
129 X Coefficient(s)  0.005586
130 Std Err of Coef.  0.000478
131
132
23-Mar-88  09:06 PM

BW5:                                                                                     READY


           AG          AH          AI          AJ          AK          BU          BV          BW
5

              log[NEUTRON LOG] vs [DENSITY LOG]
              Regression Output:
8   Constant                       2.423573
9   Std Err of Y Est               0.042476
    R Squared                      0.707138  R=0.84
11  No. of Observations                 105
12  Degrees of Freedom                  103
13
14  X Coefficient(s)  0.415457
```

```
 19           Regression Output:
 20  Constant                          403.4675
 21  Std Err of Y Est                  24.97695
 22  R Squared                         0.430050  R=0.656
 23  No. of Observations                    105
     Degrees of Freedom                     103
 -Mar-88  09:08 PM

BW25:                                                                      READY

       AG         AH         AI         AJ         AK         BU         BV         BW
 25
 26  X Coefficient(s)  -136.563
 27  Std Err of Coef.  15.49082
 28
 29
 30           [SONIC LOG] vs [DENSITY LOG]
 31           Regression Output:
 32  Constant                          1184.357
 33  Std Err of Y Est                  58.23878
 34  R Squared                         0.457960  R=0.677
 35  No. of Observations                    105
 36  Degrees of Freedom                     103
 37
 38  X Coefficient(s)  -336.949
 39  Std Err of Coef.  36.11997
 40
 41
 42           [RESISTIVITY] vs [DENSITY LOG]
 43           Regression Output:
     Constant                          -56.1810
23-Mar-88  09:08 PM

3W45:                                                                      READY

       AG         AH         AI         AJ         AK         BU         BV         BW
 45  Std Err of Y Est                  9.253738
 46  R Squared                         0.238777  R=0.489
 47  No. of Observations                    105
 48  Degrees of Freedom                     103
 49
 50  X Coefficient(s)  32.62211
 51  Std Err of Coef.  5.739212
 52
 53
 54           [NEUTRON LOG] vs [DENSITY LOG]
 55           Regression Output:
 56  Constant                          -2553.98
 57  Std Err of Y Est                  237.6640
 58  R Squared                         0.676976  R=0.823
 59  No. of Observations                    105
 60  Degrees of Freedom                     103
 61
 62  X Coefficient(s)  2165.644
 63  Std Err of Coef.  147.4004

 -Mar-88  09:08 PM

W65:                                                                       READY
```

```
66              log[SONIC] vs DENSITY LOG
 67             Regression Output:
 68  Constant                       3.435219
 69  Std Err of Y Est               0.061364
 70  R Squared                      0.467049  R=0.683
 71  No. of Observations                 105
     Degrees of Freedom                  103

 74  X Coefficient(s)   -0.36158
 75  Std Err of Coef.   0.038058
 76
 77
 78             log[RESIST] vs DENSITY LOG
 79             Regression Output:
 30  Constant                       -0.65685
 31  Std Err of Y Est               0.222525
 82  R Squared                      0.249509  R=0.50
 33  No. of Observations                 105
 34  Degrees of Freedom                  103
23-Mar-88  09:08 PM

3W85:                                                                     READY


        AG       AH       AI       AJ       AK       BU       BV       BW
35
86   X Coefficient(s)  0.807614
37   Std Err of Coef.  0.138011
38
89
90             log[SONIC] vs log[DENLOG]
?1             Regression Output:
     Constant                       3.239445
9    Std Err of Y Est               0.062888
?4   R Squared                      0.440263  R=0.664
?5   No. of Observations                 105
96   Degrees of Freedom                  103
?7
?8   X Coefficient(s)  -1.75881
?9   Std Err of Coef.  0.195405
100
.01
.02            log[RESIST] vs log[DENLOG]
103            Regression Output:
 04 Constant                        -0.20738
:3-Mar-88  09:08 PM

RW105:                                                                    READY


        AG       AH       AI       AJ       AK       BU       BV       BW
 05 Std Err of Y Est                0.225249
 06 R Squared                       0.231020  R=0.48
107 No. of Observations                  105
'08 Degrees of Freedom                   103
 09
110 X Coefficient(s)   3.893308
111 Std Err of Coef.   0.699894

-              SONIC vs log[DENLOG]
114            Regression Output:
 15 Constant                        1003.163
 16 Std Err of Y Est                59.53431
```

```
120
121 X Coefficient(s)   -1642.54
122 Std Err of Coef.   184.9846
123
124           RESIST vs log[DENLOG]
23-Mar-88  09:09 PM
W125:                                                                    READY

        AG        AH        AI        AJ        AK        BU        BV        BW
125            Regression Output:
126 Constant                       -38.0370
127 Std Err of Y Est                9.360116
128 R Squared                       0.221175  R=0.47
129 No. of Observations                  105
130 Degrees of Freedom                   103
131
132 X Coefficient(s)   157.2957
133 Std Err of Coef.   29.08369
134
135
136
137
138
139
140
141
142
143
144
23-Mar-88  09:09 PM
```

```
AC25:                                                                                READY

        I         J         K         L         M         AC        AD        AE
2
                  [WC vs GAMMA]
3                 Regression Output:
9           Constant                           -8.28357
10          Std Err of Y Est                    7.064917
11          R Squared                           0.519323 , R = 0.72
12          No. of Observations                       81
13          Degrees of Freedom                        79
14
15          X Coefficient(s)   0.233995
16          Std Err of Coef.   0.025328
17
18                [WC vs DENSITY LOG]
19                Regression Output:
20          Constant                            141.8557
21          Std Err of Y Est                    5.234107
22          R Squared                           0.736170 , R = 0.86
23          No. of Observations                       81
24          Degrees of Freedom                        79
25
21-Feb-88  08:58 PM

AC44:                                                                                READY

        I         J         K         L         M         AC        AD        AE
2
            X Coefficient(s)  -56.9978
27          Std Err of Coef.   3.838993
28
29                [WC vs NEUTRON]
30                Regression Output:
31          Constant                            58.65095
32          Std Err of Y Est                    6.121070
33          R Squared                           0.639177 , R = 0.80
34          No. of Observations                       81
35          Degrees of Freedom                        79
36
37          X Coefficient(s)  -0.01916
38          Std Err of Coef.   0.001619
39
40                [WC vs SONIC]
41                Regression Output:
42          Constant                           -20.5822
43          Std Err of Y Est                    7.631422
44          R Squared                           0.439146 , R = 0.66
21-Feb-88  08:58 PM
```

```
AC43:
                                                                        READY

           I        J        K        L        M        AC       AD       AE
 3              Std Err of Y Est                7.631422
44              R Squared                       0.439146
45              No. of Observations                   81
46              Degrees of Freedom                    79
47
48              X Coefficient(s)  0.080048
49              Std Err of Coef.  0.010177
50
51                       [WC vs RESIST]
52                       Regression Output:
53              Constant                        22.73149
54              Std Err of Y Est                8.280528
55              R Squared                       0.339679 , R=0.58
56              No. of Observations                   81
57              Degrees of Freedom                    79
58
59              X Coefficient(s)  -0.52421
60              Std Err of Coef.  0.082231
61
21-Feb-88  09:00 PM
```

```
AC62:
                                                                        READY

           I        J        K        L        M        AC       AD       AE
62                       [log(WC) vs NEUTRON]
63                       Regression Output:
64              Constant                        2.796850
65              Std Err of Y Est                0.183972
66              R Squared                       0.757387 , R=0.87
67              No. of Observations                   81
68              Degrees of Freedom                    79
69
70              X Coefficient(s)  -0.00076
71              Std Err of Coef.  0.000048
72
73                       [log(WC) vs DENSITY LOG]
74                       Regression Output:
75              Constant                        5.765297
76              Std Err of Y Est                0.184095
77              R Squared                       0.757064 , R=0.87
78              No. of Observations                   81
79              Degrees of Freedom                    79
80
21-Feb-88  09:00 PM
```

```
AC90:
                                                                        READY

           I        J        K        L        M        AC       AD       AE

73                       [log(WC) vs DENSITY LOG]
74                       Regression Output:
 5              Constant                        5.765297
```

```
79            Degrees of Freedom                79
80
81            X Coefficient(s)  -2.11861
82            Std Err of Coef.   0.135025
83
84
85
86
87
88
89
90
21-Feb-88  09:00 PM
```

```
AN6:                                                                    READY

          AH          AI          AJ         AK          AL       AM       AN
 1
 4
 5
 6
 7  [Qu vs N*D]
 8           Regression Output:
 9  Constant                                 -85.63
10  Std Err of Y Est                          12.18
11  R Squared                                  0.61 , R = 0.78
12  No. of Obs                                58.00
13  Degrees of Freedom                        56.00
14
15  X Coefficient(s)            0.02
16  Std Err of Coef.            0.00
17
18
19           Regression Output:
20  Constant                                -893.67
20-Feb-88  08:58 PM                                  CALC
```

```
G10:                                                                READY

         AB          AC          AD          AE          AF          AG
1

4
5   en]
6             log[Qu] vs log[Neut*Den]
7             Regression Output:
8   Constant                                   -28.20
9   Std Err of Y Est                             0.45
10  R Squared                                    0.59  , R=0.77
11  No. of Observations                         59.00
12  Degrees of Freedom                          57.00
13
14  X Coefficient(s)                 7.69
15  Std Err of Coef.                 0.85
16
17
18
19
20
6-Mar-88   11:33 PM                                  CALC
```

```
7:                                                                  READY

       V          W          X          Y          Z          AA          AB
                Qu vs Neutron LOG                             3.8474
                Regression Output:                            3.7086 Constant
9   Constant                             -79.82               3.7073 Std Err of Y
10  Std Err of Y Est                      14.31               3.7790 R Squared
11  R Squared                              0.48  R: 0.69      3.8028 No. of Obser
12  No. of Observations                   59.00               3.7010 Degrees of F
13  Degrees of Freedom                    57.00               3.6858
14                                                            3.7359 X Coefficien
15  X Coefficient(s)            0.04                          3.7841 Std Err of C
16  Std Err of Coef.            0.01                          3.8966
17                                                            3.6849
18              Qu vs log[Neutron Log]                        3.8945
19              Regression Output:                            3.8769
20  Constant                            -827.17               3.8274
21  Std Err of Y Est                      13.93               3.7002
22  R Squared                              0.50  R=0.71       3.6945
23  No. of Observations                   59.00               3.7311
24  Degrees of Freedom                    57.00               3.8131
25                                                            3.7346
26  X Coefficient(s)          247.78                          3.7237
6-Mar-88   11:35 PM                                 CALC
```

```
Z27:                                                                READY

       V          W          X          Y          Z          AA          AB
27  Std Err of Coef.           32.63                          3.8668
                                                              3.8519
29              log[Qu] vs log[Neutron Log]                   3.7522
30              Regression Output:                            3.7416
31  Constant                             -27.82               3.7522
32  Std Err of Y Est                       0.51               3.7607
```

```
36                                                                3.7385
37  X Coefficient(s)        8.41                                  3.8203
38  Std Err of Coef.        1.19                                  3.7221
39                                                                3.7356
40             log[Qu] vs Neutron*Density Log                     3.7937
41             Regression Output:                                 3.7663
42  Constant                               -13.69                 3.8681
43  Std Err of Y Est                         0.37                 3.7602
44  R Squared                                0.72  R=0.85         3.8513
45  No. of Observations                     59.00                 3.7213
46  Degrees of Freedom                      57.00                 3.7690
16-Mar-88  11:35 PM                                         CALC

Z47:                                                                            READY

         V          W          X          Y          Z          AA          AB
47                                                              3.8547
48  X Coefficient(s)        6.21                                3.7178
49  Std Err of Coef.        0.51                                3.8350
50                                                              3.7417
51             log[Qu] vs log[Neutron*Density]                  3.7221
52                                                              3.8532
53                                                              3.8783
54                                                              3.7802
55                                                              3.8079
56                                                              3.6690
57                                                              3.7626
58                                                              3.8543
59                                                              3.7503
60                                                              3.7269
61                                                              3.8131
                                                                3.7174
                                                                3.7054
64                                                              3.7125
65
66
16-Mar-88  11:36 PM                                         CALC
```

```
AI25:                                                                    READY

          I         J         K         L         M         N         AH        AI
3                        LL vs GAMMA
                         Regression Output:
        Constant                                -53.1689
9       Std Err of Y Est                        87.54253
10      R Squared                               0.178910 R=0.42
11      No. of Observations                           52
12      Degrees of Freedom                            50
13
14      X Coefficient(s)   1.545520
15      Std Err of Coef.   0.468237
16
17
18                       LL vs DENLOG
19                       Regression Output:
20      Constant                                993.7857
21      Std Err of Y Est                        78.19391
22      R Squared                               0.344914 R=0.59
23      No. of Observations                           52
24      Degrees of Freedom                            50
25
27-Mar-88  05:32 PM

AI45:                                                                    READY

          I         J         K         L         M         N         AH        AI
26      X Coefficient(s)   -402.779
        Std Err of Coef.   78.50096
28
29
30                       LL vs NEUTRON
31                       Regression Output:
32      Constant                                425.0567
33      Std Err of Y Est                        91.89492
34      R Squared                               0.095236 R=0.31
35      No. of Observations                           52
36      Degrees of Freedom                            50
37
38      X Coefficient(s)   -0.14798
39      Std Err of Coef.   0.064504
40
41
42                       LL vs SONIC
43                       Regression Output:
44      Constant                                77.59615
45      Std Err of Y Est                        96.38410
27-Mar-88  05:33 PM

AI65:                                                                    READY

          I         J         K         L         M         N         AH        AI
46      R Squared                               0.004679 R=0.07
        No. of Observations                           52
48      Degrees of Freedom                            50
49
50      X Coefficient(s)   0.121117
51      Std Err of Coef.   0.249800
```

```
 55                       Regression Output:
 56         Constant                                129.3878
 57         Std Err of Y Est                        96.57546
 58         R Squared                               0.000723 R=0.03
 59         No. of Observations                           52
 60         Degrees of Freedom                            50

            X Coefficient(s)  0.617918
 63         Std Err of Coef.  3.247476
 64
 65
27-Mar-88  05:33 PM

A025:                                                                        READY


        V         W         X         Y         Z         AA        AB        AO
 6                       PI vs GAMMA
 7                       Regression Output:
 8          Constant                                -53.8494
 9          Std Err of Y Est                        82.71658
 10         R Squared                               0.151419 R=0.39
 11         No. of Observations                           52
 12         Degrees of Freedom                            50
 13
 14         X Coefficient(s)  1.321505
 15         Std Err of Coef.  0.442425
 16
 17
 18                      PI vs DenLog
 19                      Regression Output:
 20         Constant                                886.3669
            Std Err of Y Est                        73.56343
            R Squared                               0.328830 R=0.57
 23         No. of Observations                           52
 24         Degrees of Freedom                            50
 25
27-Mar-88  05:35 PM

A045:                                                                        READY


        V         W         X         Y         Z         AA        AB        AO
 26         X Coefficient(s)  -365.526
 27         Std Err of Coef.  73.85231
 28
 29
 30                      PI vs NEUTRON
 31                      Regression Output:
 32         Constant                                349.7601
 33         Std Err of Y Est                        86.25874
 34         R Squared                               0.077186 R=0.28
 35         No. of Observations                           52
 36         Degrees of Freedom                            50
 37
 38         X Coefficient(s)  -0.12382
 39         Std Err of Coef.  0.060548
 40


                         LL vs DenLog/GAMMA
 43                      Regression Output:
 44         Constant                                294.0664
 45         Std Err of Y Est                        86.48093
```

```
          V          W          X          Y          Z          AA         AB         AO
 46             R Squared                          0.198704 R=0.45
 47             No. of Observations                     52
 48             Degrees of Freedom                      50

                X Coefficient(s)   -8591.57
 51             Std Err of Coef.   2439.946
 52
 53
 54                       LL vs DenLog*GAMMA
 55                       Regression Output:
 56             Constant                           7.105132
 57             Std Err of Y Est                   93.53256
 58             R Squared                          0.062701 R=0.25
 59             No. of Observations                     52
 60             Degrees of Freedom                      50
 61
 62             X Coefficient(s)   0.497685
 63             Std Err of Coef.   0.272125
 64
 65
27-Mar-88  05:35 PM

AI26:                                                                                READY


          AB         AC         AD         AE         AF         AG         AH         AI
 7                        log[LL] vs GAMMA
 8                        Regression Output:
 9              Constant                           1.582628
                Std Err of Y Est                   0.221929
 11             R Squared                          0.177072 R=0.42
 12             No. of Observations                     52
 13             Degrees of Freedom                      50
 14
 15             X Coefficient(s)   0.003893
 16             Std Err of Coef.   0.001187
 17
 18
 19                       log[LL] vs NEUTRON
 20                       Regression Output:
 21             Constant                           2.957169
 22             Std Err of Y Est                   0.226439
 23             R Squared                          0.143281 R=0.38
 24             No. of Observations                     52
 25             Degrees of Freedom                      50
 26
27-Mar-88  05:36 PM

AI46:                                                                                READY


          AB         AC         AD         AE         AF         AG         AH         AI
 27             X Coefficient(s)   -0.00045
 28             Std Err of Coef.   0.000158
 29


                          log[LL] vs DENLOG
 32                       Regression Output:
 33             Constant                           4.207283
 34             Std Err of Y Est                   0.199152
 39          X Coefficient(s)  -1.00865
 40          Std Err of Coef.  0.199934
 41
 42
 43                    log[LL] vs log[DENLOG]
 44                   Regression Output:
             Constant                          3.652961
 46          Std Err of Y Est                  0.198568
27-Mar-88  05:37 PM

AI66:
                                                                          READY

        AB       AC        AD       AE       AF       AG       AH       AI
 47          R Squared                         0.341199 R=0.58
 48          No. of Observations                     52
 49          Degrees of Freedom                      50
 50
 51          X Coefficient(s)  -4.86842
 52          Std Err of Coef.  0.956702
 53
 54
 55                   log[LL] vs log[NEUTRON]
 56                   Regression Output:
 57          Constant                          8.770699
 58          Std Err of Y Est                  0.227268
 59          R Squared                         0.137002 R=0.37
 60          No. of Observations                     52
 61          Degrees of Freedom                      50
 62
 63          X Coefficient(s)  -2.04080
             Std Err of Coef.  0.724364

 66
27-Mar-88  05:37 PM

AI86:
                                                                          READY

        AB       AC        AD       AE       AF       AG       AH       AI
 67                   LL vs log[NEUTRON]
 68                   Regression Output:
 69          Constant                          2300.727
 70          Std Err of Y Est                  92.08967
 71          R Squared                         0.091397 R=0.30
 72          No. of Observations                     52
 73          Degrees of Freedom                      50
 74
 75          X Coefficient(s)  -658.256
 76          Std Err of Coef.  293.5147
 77
 78
 79
 80
 81
 82
 83


 86
27-Mar-88  05:37 PM
```

```
 6                              LL vs log(DENLOG)
 7                              Regression Output:
 8                     Constant                          779.9527
 9                     Std Err of Y Est                  77.45903
10                     R Squared                         0.357169 R=0.60
11                     No. of Observations                     52
                       Degrees of Freedom                      50
13
14                     X Coefficient(s)   -1967.03
15                     Std Err of Coef.    373.1971
16
17
18                              LL vs log(GAMMA)
19
20                              Regression Output:
21                     Constant                          -686.797
22                     Std Err of Y Est                  88.51227
23                     R Squared                         0.160619 R=0.40
24                     No. of Observations                     52
25                     Degrees of Freedom                      50
27-Mar-88  05:38 PM

A045:                                                                          READY

           AH        AI        AJ        AK        AL        AM        AN        AO
26
27                     X Coefficient(s)   396.0333
28                     Std Err of Coef.   128.0347
29
30
                                PI vs log(DENLOG)
                                Regression Output:
33                     Constant                          693.1834
34                     Std Err of Y Est                  72.86407
35                     R Squared                         0.341531 R=0.58
36                     No. of Observations                     52
37                     Degrees of Freedom                      50
38
39                     X Coefficient(s)   -1787.77
40                     Std Err of Coef.    351.0585
41
42
43                              PI vs log(NEUTRON)
44                              Regression Output:
45                     Constant                          1914.267
27-Mar-88  05:38 PM

A065:                                                                          READY

           AH        AI        AJ        AK        AL        AM        AN        AO
46                     Std Err of Y Est                  86.42285
47                     R Squared                         0.073671 R=0.27
48                     No. of Observations                     52
49                     Degrees of Freedom                      50
50
                       X Coefficient(s)   -549.286
                       Std Err of Coef.   275.4530
53
54
55                              PI vs log(GAMMA)
```

```
            No. of Observations                  52
48          Degrees of Freedom                   50
49
50          X Coefficient(s)  -626.337
51          Std Err of Coef.  176.7714
52


                    LL vs DenLog*neut/Gamma
55                  Regression Output:
56          Constant                        245.1507
57          Std Err of Y Est                87.79723
58          R Squared                       0.174126 R=0.42
59          No. of Observations                   52
60          Degrees of Freedom                    50
61
62          X Coefficient(s)  -2.97014
63          Std Err of Coef.  0.914781
64
65
27-Mar-88  05:40 PM

U25:                                                                        READY


       AY        AZ        BA        BB        BC        BD        BU        BV
                    LL vs Den*Gamma/Neut
7                   Regression Output:
8           Constant                        25.83007
9           Std Err of Y Est                92.54563
10          R Squared                       0.082377 R=0.29
11          No. of Observations                   52
12          Degrees of Freedom                    50

14          X Coefficient(s)  814.6648
15          Std Err of Coef.  384.5215
16
17
18                  LL vs (D*N*R/S*G)
19                  Regression Output:
20          Constant                        173.2970
21          Std Err of Y Est                92.69352
22          R Squared                       0.079442 R=0.28
23          No. of Observations                   52
24          Degrees of Freedom                    50
25
27-Mar-88  05:41 PM

BU45:                                                                       READY


       AY        AZ        BA        BB        BC        BD        BU        BV
26          X Coefficient(s)  -43.9885
27          Std Err of Coef.  21.17643
28
29
30                  LL vs D*N*R/G
31                  Regression Output:
32          Constant                        179.4970
            Std Err of Y Est                92.28702
            R Squared                       0.087499 R=0.30
35          No. of Observations                   52
36          Degrees of Freedom                    50
37
```

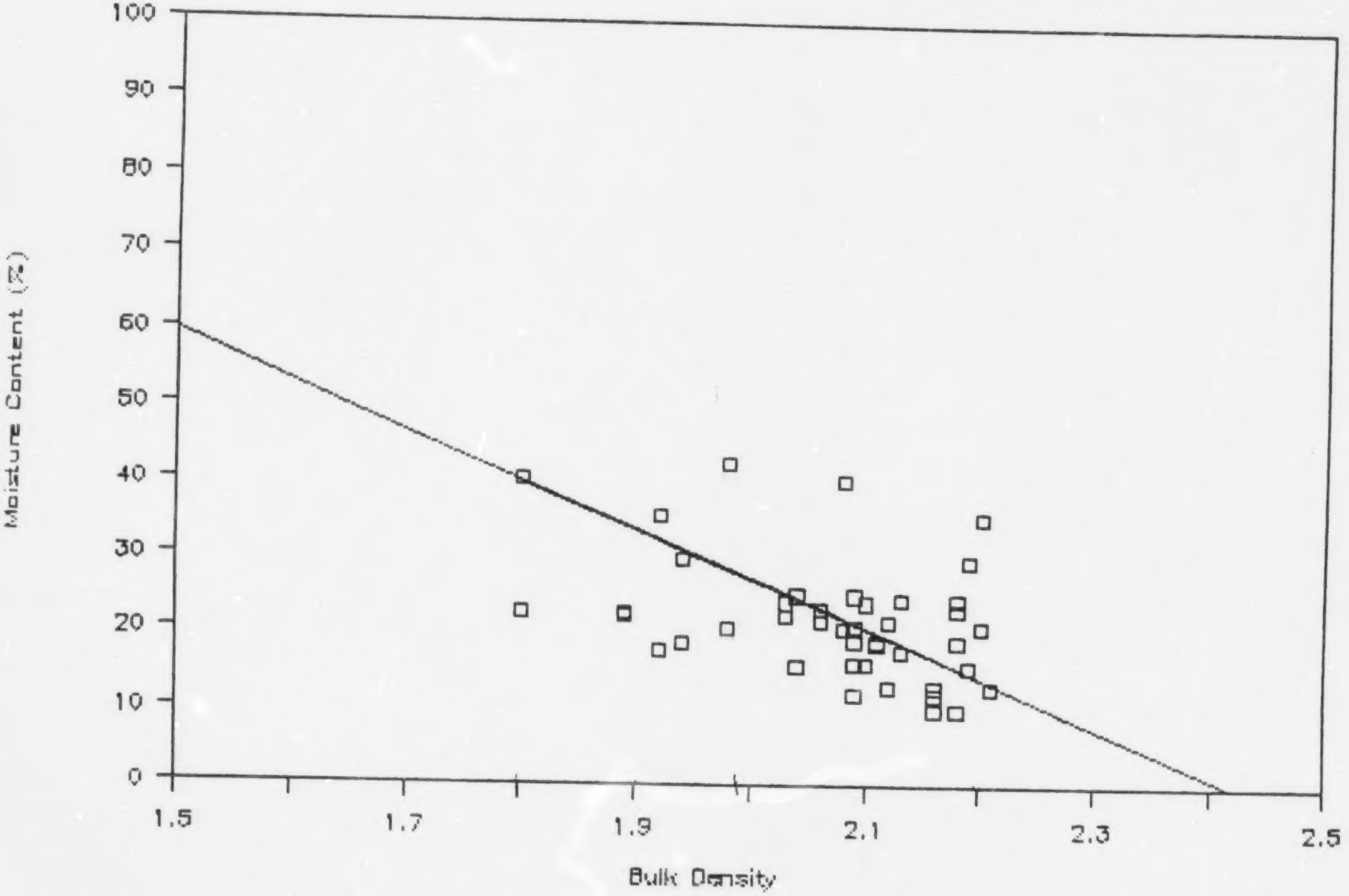
```
 42                     LL vs D*N*R
 43                     Regression Output:
 44           Constant                            175.8010
 45           Std Err of Y Est                    94.87121
27-Mar-88  05:42 PM

 65:                                                                        READY

          AY          AZ          BA          BB          BC          BD          BU          BV
 46           R Squared                           0.035680 R=0.19
 47           No. of Observations                       52
 48           Degrees of Freedom                        50
 49
 50           X Coefficient(s)  -0.00092
 51           Std Err of Coef.  0.000682
 52
 53
 54
 55
 56
 57
 58
 59
 60
 61
 62
  3
 64
 65
 7-Mar-88  05:42 PM

  5:                                                                        READY

          BJ          BK          BL          BM          BN          BP          BQ          BR
 6             LL vs Gamma/DenLog
               Regression Output:
     Constant                      -57.5093
 9   Std Err of Y Est              82.07925
 0   R Squared                     0.278196 R=0.53
 1   No. of Observations                 52
 12  Degrees of Freedom                  50
 13
 4   X Coefficient(s)  3.327310
 15  Std Err of Coef.  0.757952
 16
 7
 3             LL vs Gamma/D*N
 19            Regression Output:
 20  Constant                      0.601969
 1   Std Err of Y Est              84.80868
 22  R Squared                     0.229393 R=0.48
 23  No. of Observations                 52
 4   Degrees of Freedom                  50
 25
27-Mar-88  05:43 PM

 1  :                                                                       READY

          BJ          BK          BL          BM          BN          BP          BQ          BR
     X Coefficient(s)  4414.679
```

APPENDIX IV

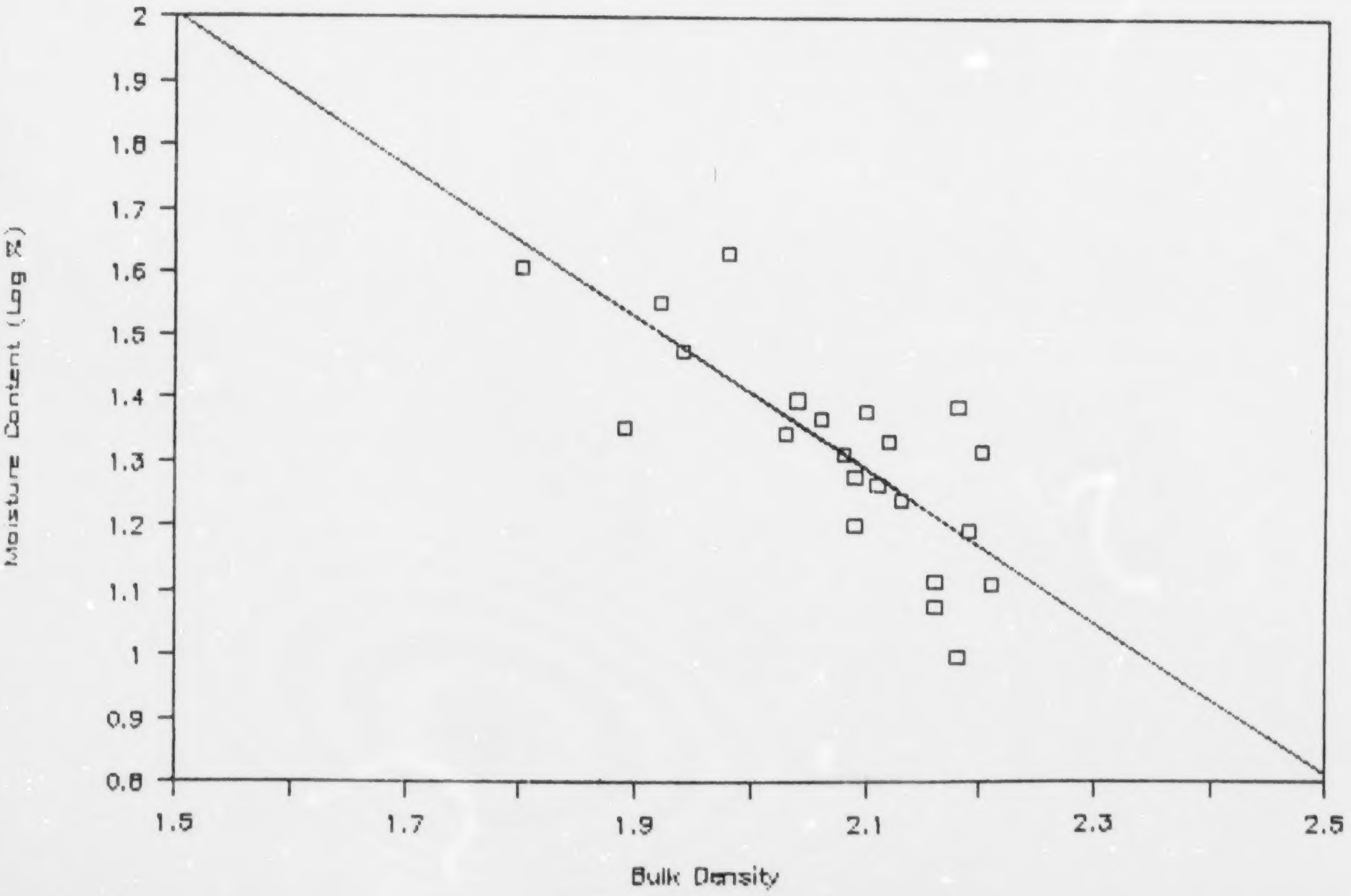
GEOTECHNICAL OIL SANDS CORRELATIONS

```
          Regression Analysis Output for
                 Moisture Content (%) vs Bulk Density Log

          Regression Output:
 Constant                    156.8910
 Std Err of Y Est            5.349495
 R Squared                   0.591290          R Value            0.768954
 No. of Observations              159
 Degrees of Freedom               157

 X Coefficient(s)  -64.8761
 Std Err of Coef.  4.304689                    Y=-64.876*X+156.891


          Regression Analysis Output for
                 Log of Moisture Content (Log %) vs Bulk Density Log


          Regression Output:
 Constant                    3.790103
 Std Err of Y Est            0.100344
 R Squared                   0.580499          R Value  0.761905
 No. of Observations              159
 Degrees of Freedom               157

 X Coefficient(s)  -1.19016
 Std Err of Coef.  0.080746                    Y=-1.190*X+3.790
```

Moisture Content(%) vs Bulk Density Log



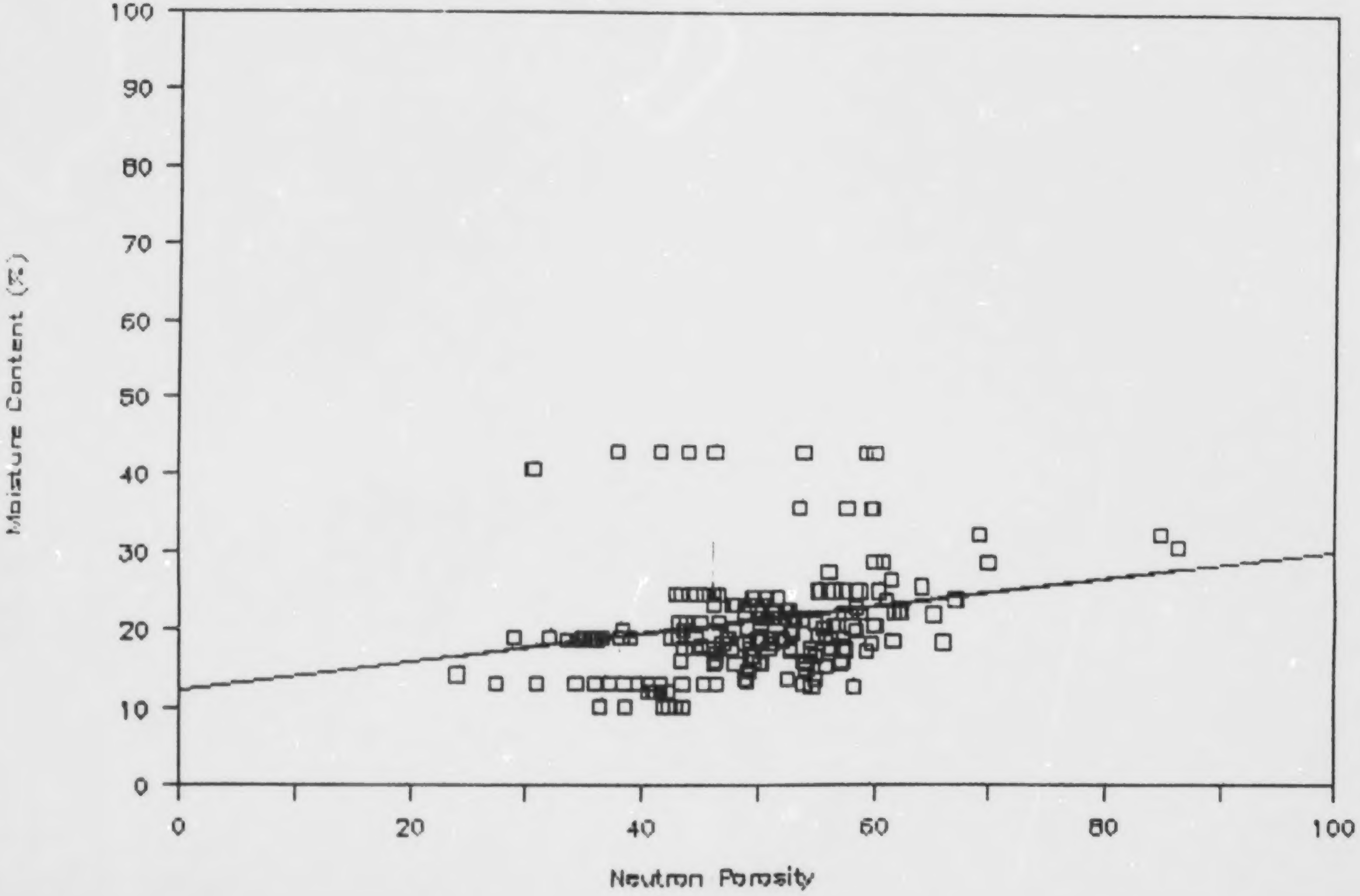
Log Water Content vs Bulk Density Log



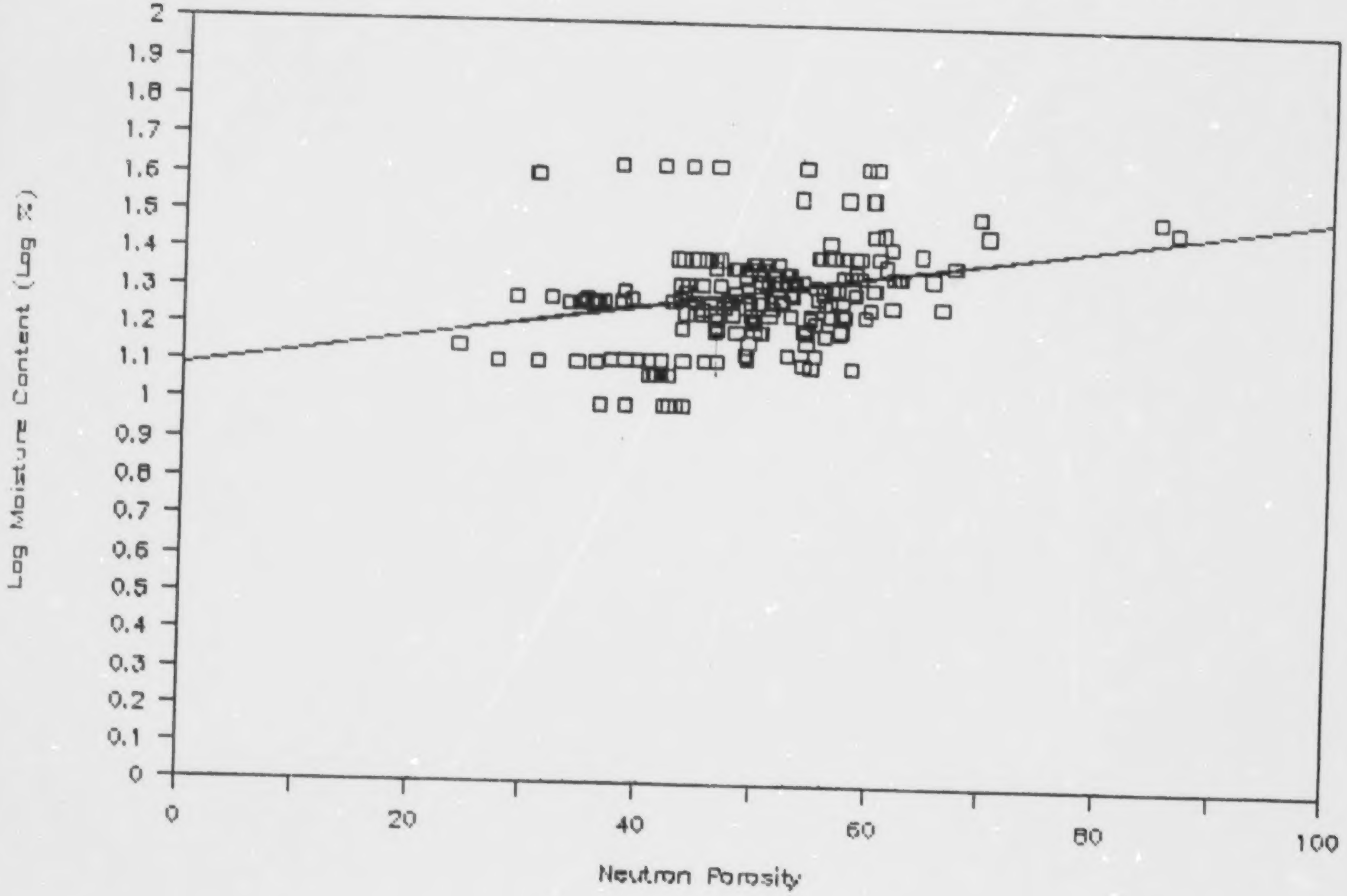
```
Regression Analysis Output for
        Moisture Content (%) vs Neutron Porosity Log


        Regression Output:
Constant                    12.26879
Std Err of Y Est            7.199949
R Squared                   0.053313           R Value  0.230896
No. of Observations              229
Degrees of Freedom               227

X Coefficient(s)  0.179679
Std Err of Coef.  0.050254                     Y=0.180*X+12.269
```

```
Regression Analysis Output for
        Log of Moisture Content (Log %) vs Neutron Porosity Log


        Regression Output:
Constant                    1.087054
Std Err of Y Est            0.131847
R Squared                   0.089626           R Value  0.299377
No. of Observations              229
Degrees of Freedom               227

X Coefficient(s)  0.004350
Std Err of Coef.  0.000920                     Y=0.004*X+1.087
```

Moisture Content(%) vs Neutron Porosity



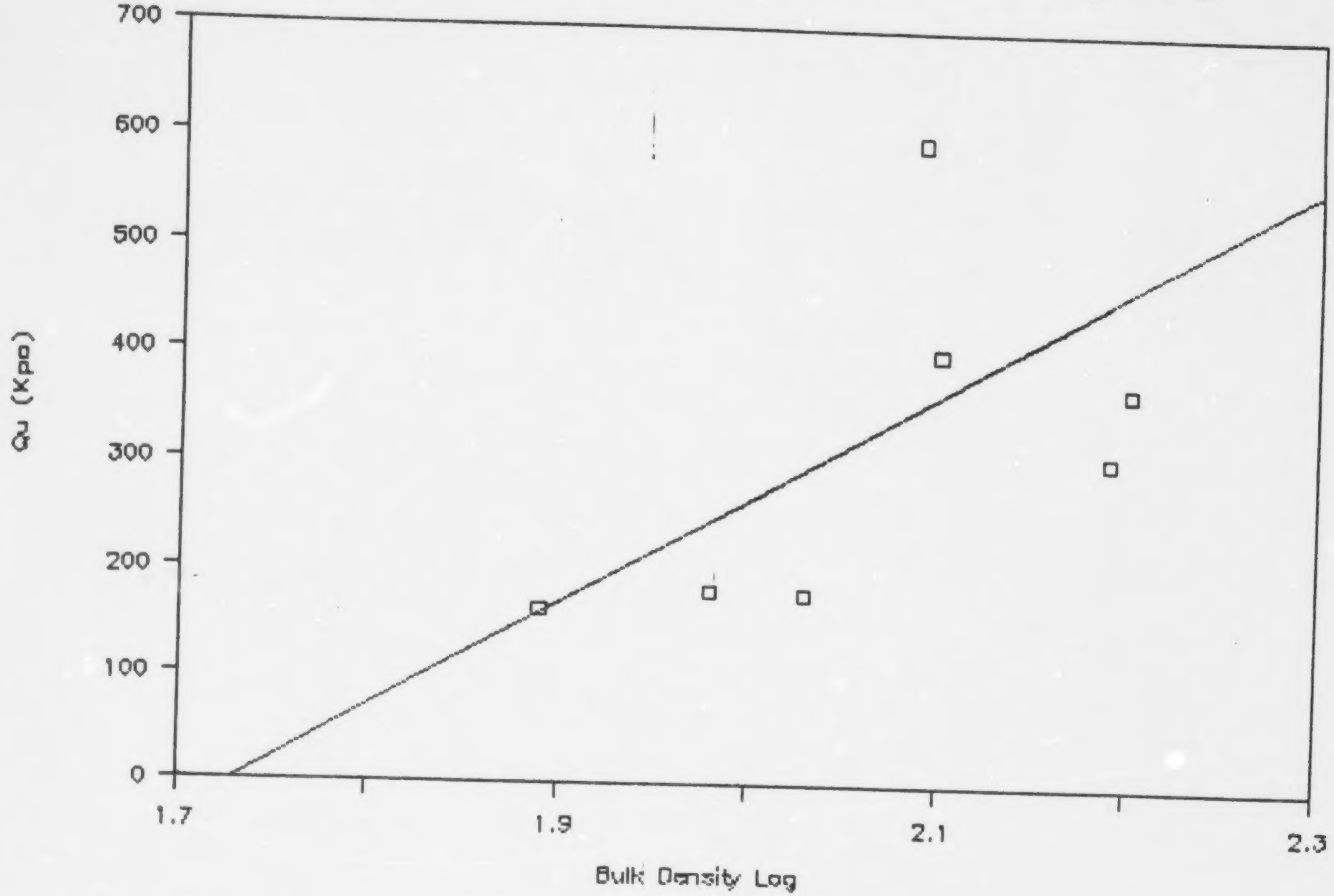
Log M.C. (Log %) vs Neutron Porosity

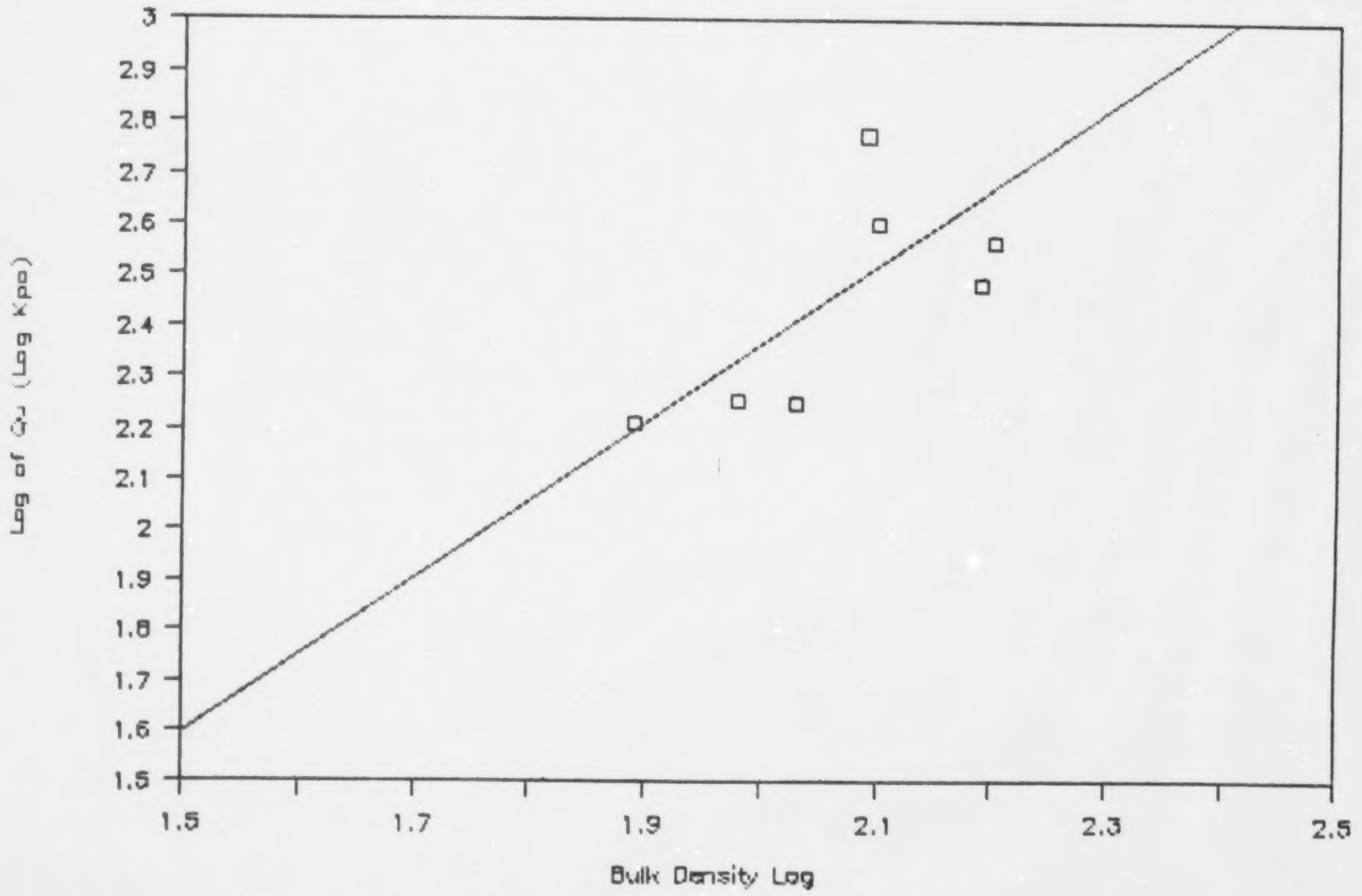


```
Regression Analysis Output for
        Undrained Shear Strength vs Bulk Density Log


        Regression Output:
Constant                        -1694.23
Std Err of Y Est                135.1809
R Squared                       0.346617          R Value    0.589
No. of Observations                   41
Degrees of Freedom                    39

X Coefficient(s)  980.3771
Std Err of Coef.  215.5359                        Y=980.377*X-1694.23
```

```
Regression Analysis Output for
        Log of Undrained Shear Strength vs Bulk Density Log


        Regression Output:
Constant                        -0.72090
Std Err of Y Est                0.159056
R Squared                       0.487176          R Value 0.697980
No. of Observations                   41
Degrees of Freedom                    39

X Coefficient(s)  1.543640
Std Err of Coef.  0.253603                        Y=1.544*X-0.721
```

Undrained Shear Strength vs Density Log

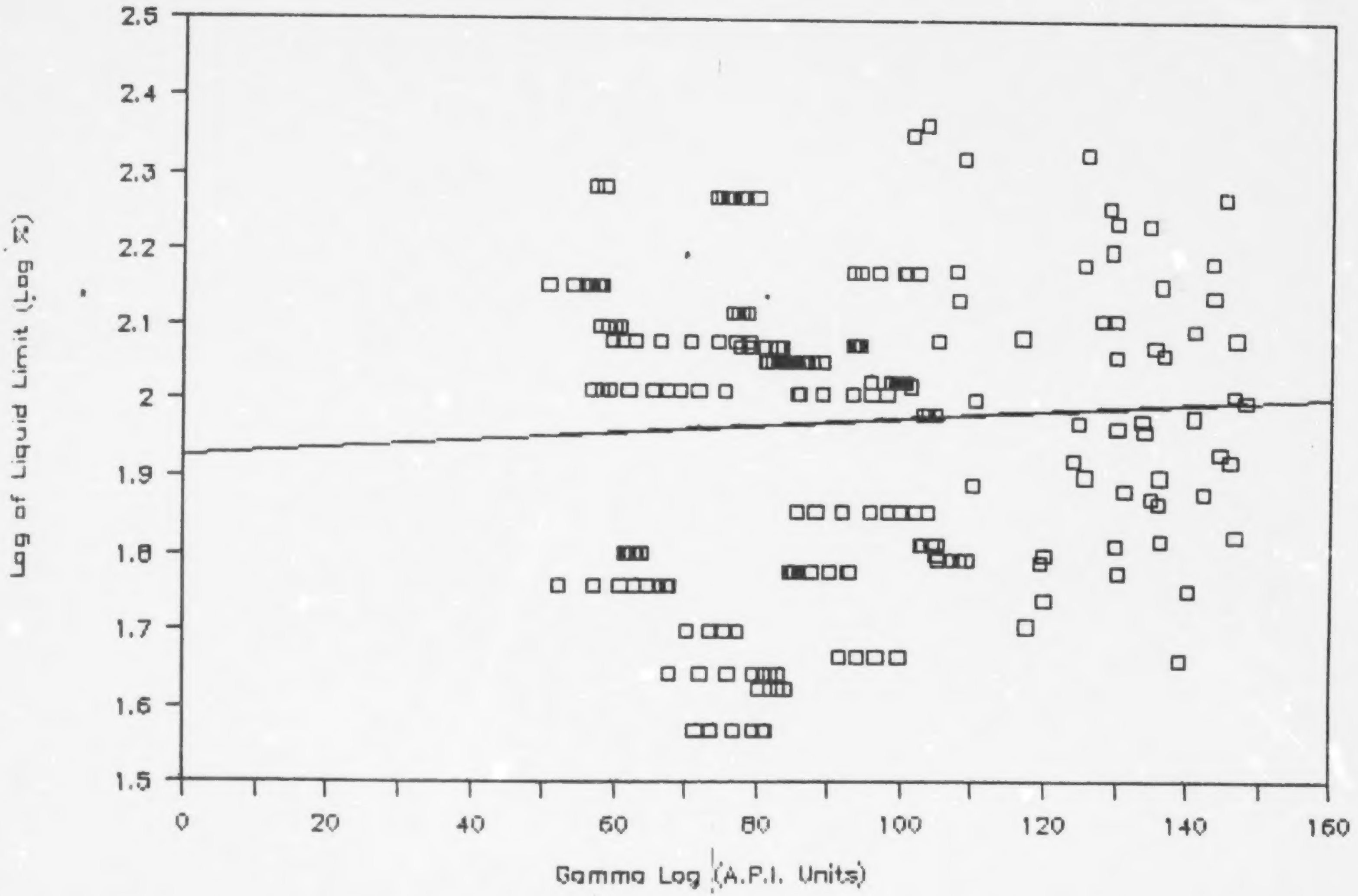




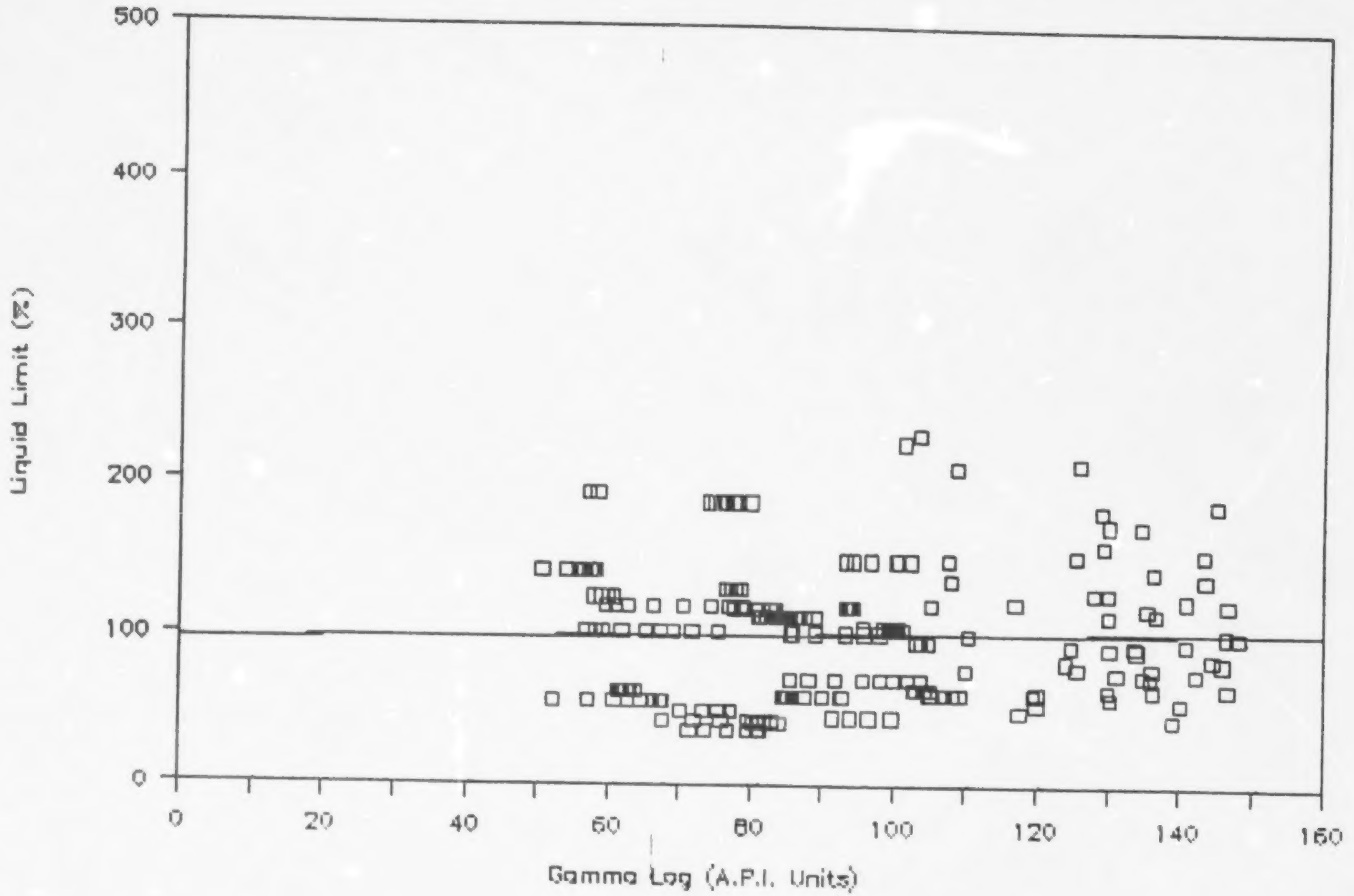
Log Of Shear Strength vs Density Log

```
Regression Analysis Output for
       Liquid Limit vs Gamma Log


       Regression Output:
Constant                     96.70594
Std Err of Y Est             42.77694
R Squared                    0.000754        R Value    0.027
No. of Observations               222
Degrees of Freedom                220

X Coefficient(s)  0.046645
Std Err of Coef.  0.114418                   Y=0.047*X=96.706


Regression Analysis Output for
       Log of Liquid Limit vs Gamma Log


       Regression Output:
Constant                     1.926361
Std Err of Y Est             0.194219
R Squared                    0.002710        R Value  0.052061
No. of Observations               222
Degrees of Freedom                220

X Coefficient(s)  0.000401
Std Err of Coef.  0.000519                   Y=0.0004*X+1.926
```

Log of Liquid Limit vs Gamma Log



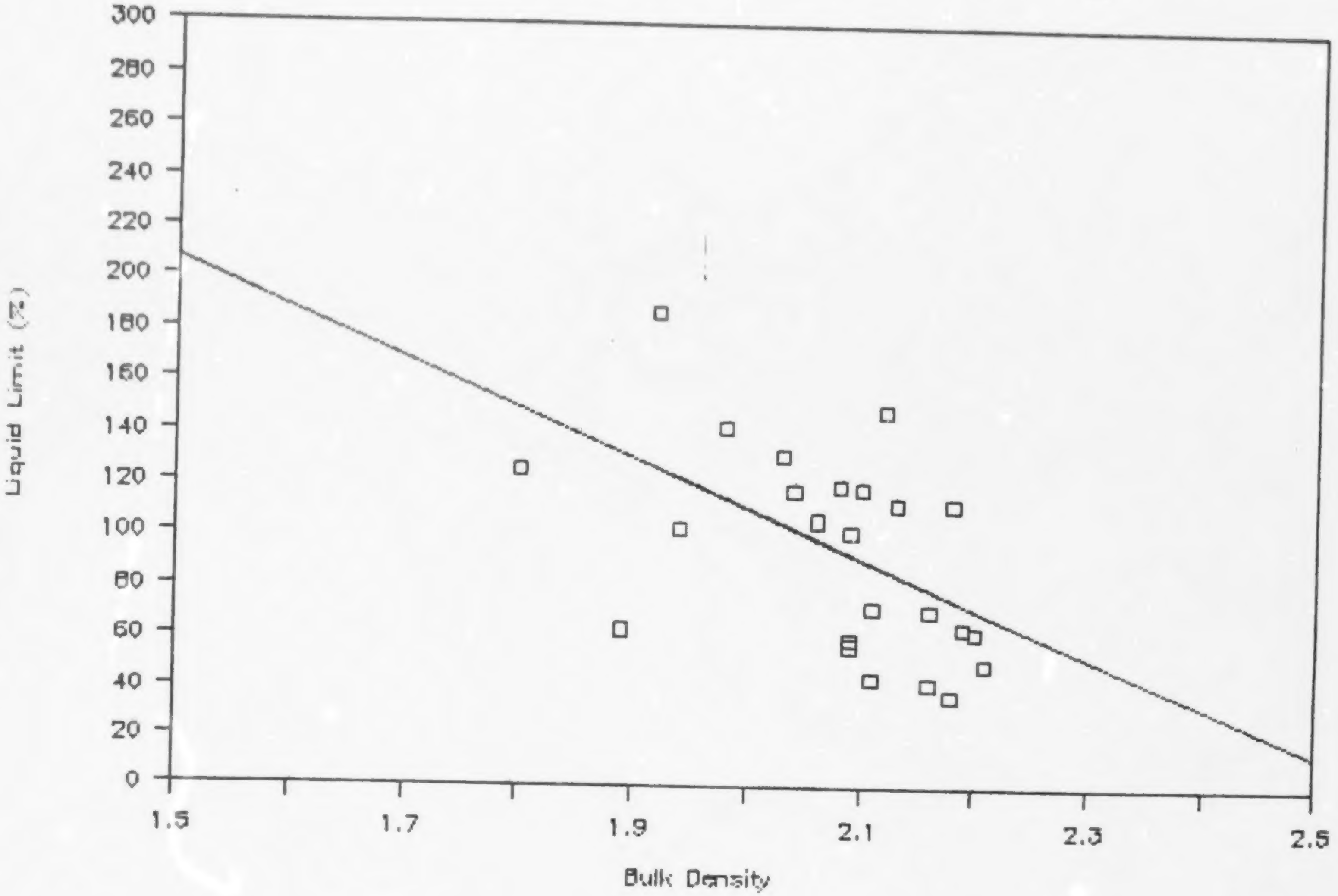
Liquid Limit vs Gamma Log



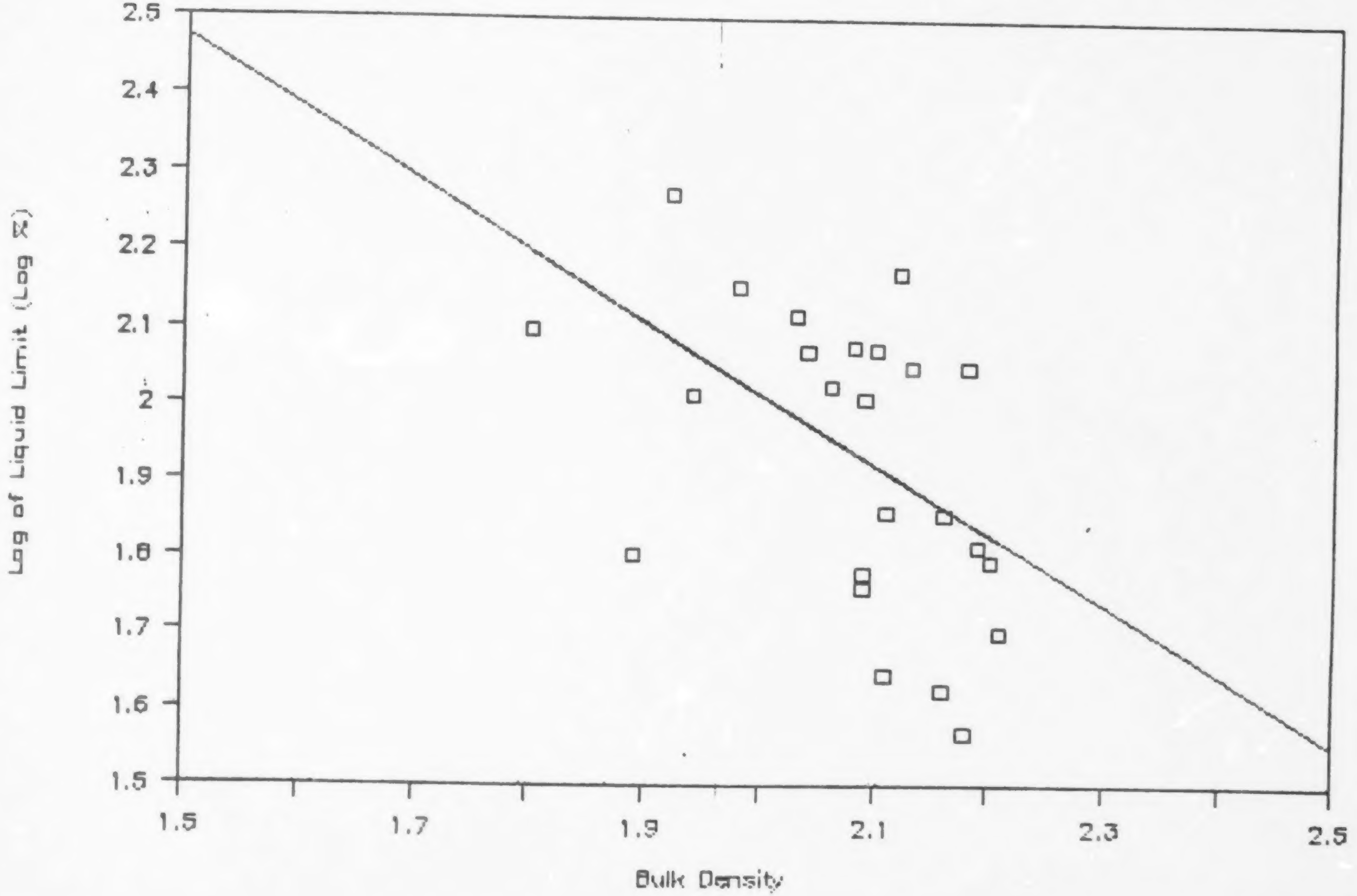
```
Regression Analysis Output for
        Liquid Limit vs Bulk Density Log


        Regression Output:
Constant                     498.2389
Std Err of Y Est             34.33036
R Squared                    0.235590          R Value  0.485376
No. of Observations               162
Degrees of Freedom                160

X Coefficient(s)  -193.705
Std Err of Coef.  27.58459                     Y=-193.705*X+498.239
```

```
Regression Analysis Output for
        Log of Liquid Limit vs Bulk Density Log


        Regression Output:
Constant                     3.858092
Std Err of Y Est             0.169406
R Squared                    0.222968          R Value  0.472195
No. of Observations               162
Degrees of Freedom                160

X Coefficient(s)  -0.92231
Std Err of Coef.  0.136118                     Y=-0.922*X+3.858
```

Liquid Limit vs Bulk Density Log

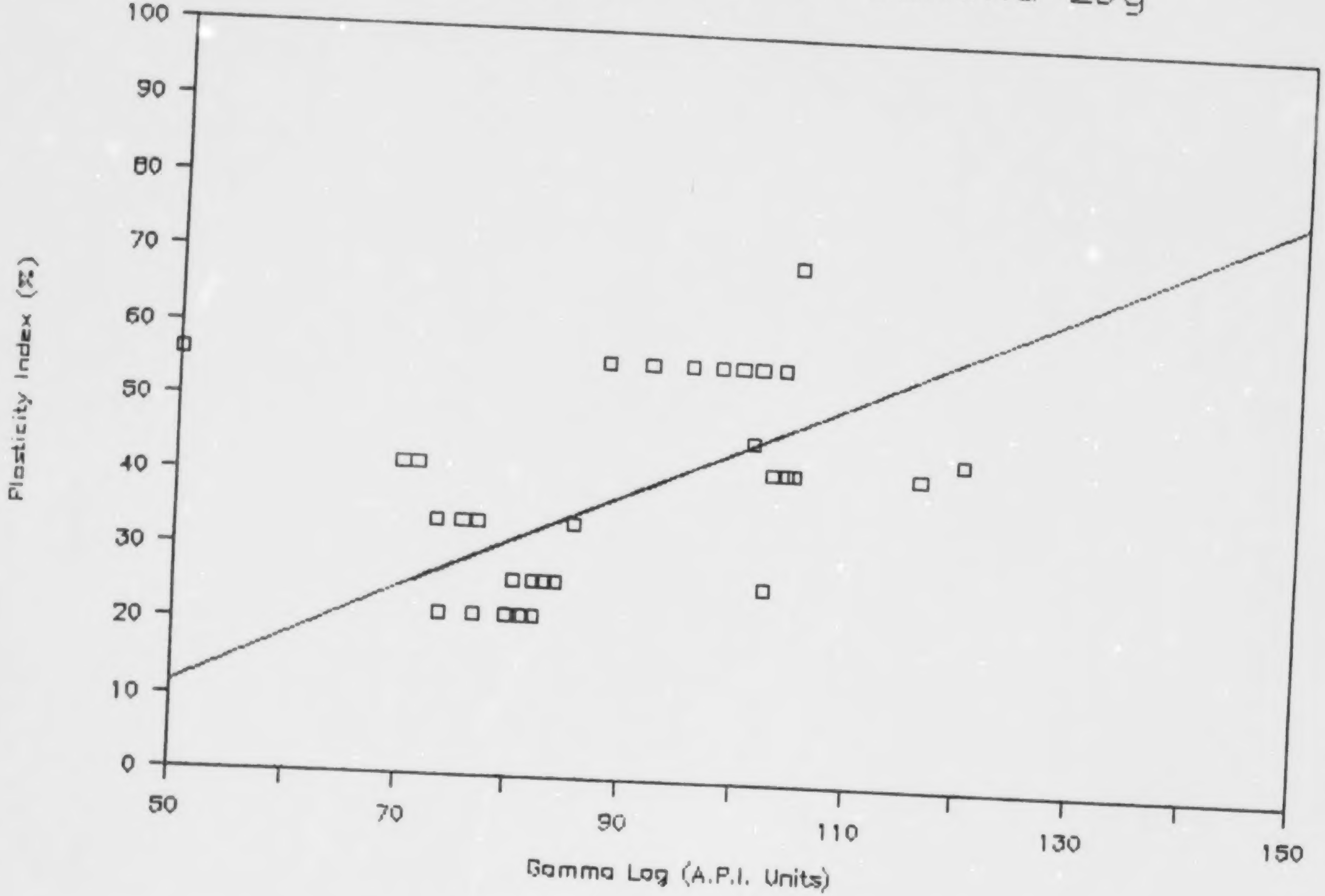


Log Of Liquid Limit vs Bulk Density Log



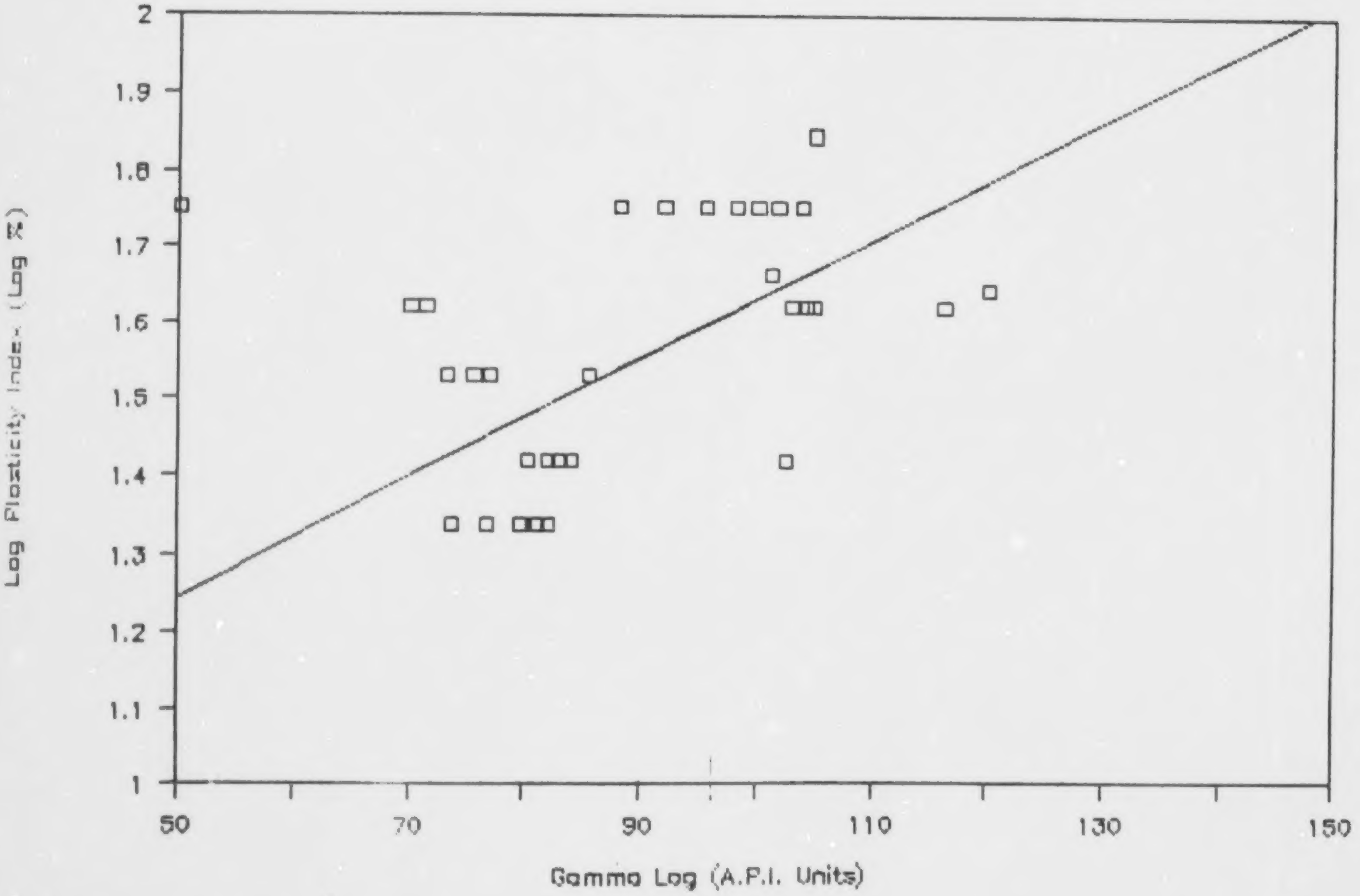
```
Regression Analysis Output for
        Plasticity Index vs Gamma Log


Strat.
Unit

Kcw              Regression Output:
        Constant                        -21.7798
        Std Err of Y Est                10.22038
        R Squared                       0.491905        R Value  0.701359
        No. of Observations                   33
        Degrees of Freedom                    31

        X Coefficient(s)  0.666664
        Std Err of Coef.  0.121690                      Y=0.667*X-21.780


Kca              Regression Output:
        Constant                        58.60003
        Std Err of Y Est                20.97062
        R Squared                       0.124522        R Value  0.352877
        No. of Observations                   59
        Degrees of Freedom                    57

        X Coefficient(s)  0.376026
        Std Err of Coef.  0.132062                      Y=0.376*X+58.600


Kcb              Regression Output:
        Constant                        75.21050
        Std Err of Y Est                41.78179
        R Squared                       0.016346        R Value  0.127854
        No. of Observations                   82
        Degrees of Freedom                    80

        X Coefficient(s)  0.248868
        Std Err of Coef.  0.215838                      Y=0.249*X+75.211


Kcc              Regression Output:
        Constant                        -6.55463
        Std Err of Y Est                23.71675
        R Squared                       0.199423        R Value  0.446568
        No. of Observations                   68
        Degrees of Freedom                    66

        X Coefficient(s)  0.491663
        Std Err of Coef.  0.121257                      Y=0.492*X-6.555
```

```
Regression Analysis Output for
         Log of Plasticity Index vs Gamma Log

 Strat.
  Unit

Kcw               Regression Output:
         Constant                          0.857887
         Std Err of Y Est                  0.115940
         R Squared                         0.502732        R Value  0.709036
         No. of Observations                     33
         Degrees of Freedom                      31

         X Coefficient(s)  0.007728
         Std Err of Coef.  0.001380                        Y=0.008*X+0.858


Kca               Regression Output:
         Constant                          1.834886
         Std Err of Y Est                  0.101731
         R Squared                         0.070840        R Value  0.266158
         No. of Observations                     59
         Degrees of Freedom                      57

         X Coefficient(s)  0.001335
         Std Err of Coef.  0.000640                        Y+0.001*X+1.835


Kcb               Regression Output:
         Constant                          1.845154
         Std Err of Y Est                  0.209151
         R Squared                         0.012491        R Value  0.111767
         No. of Observations                     82
         Degrees of Freedom                      80

         X Coefficient(s)  0.001086
         Std Err of Coef.  0.001080                        Y=0.001*X+1.845


Kcc               Regression Output:
         Constant                          1.166412
         Std Err of Y Est                  0.181695
         R Squared                         0.236108        R Value  0.485909
         No. of Observations                     68
         Degrees of Freedom                      66

         X Coefficient(s)  0.004195
         Std Err of Coef.  0.000928                        Y=0.004*X+1.166
```

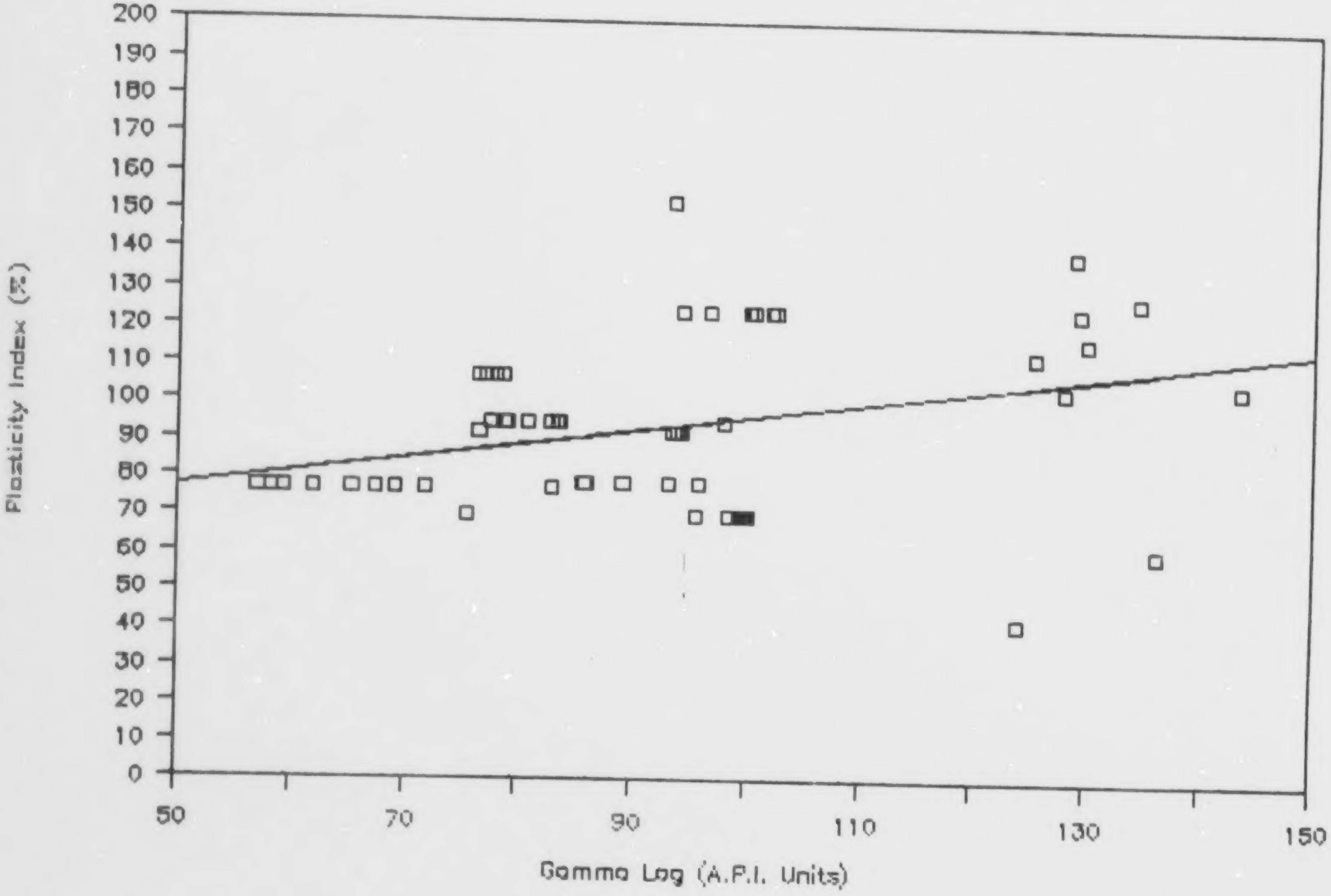


Kcw Plasticity Index vs Gamma Log

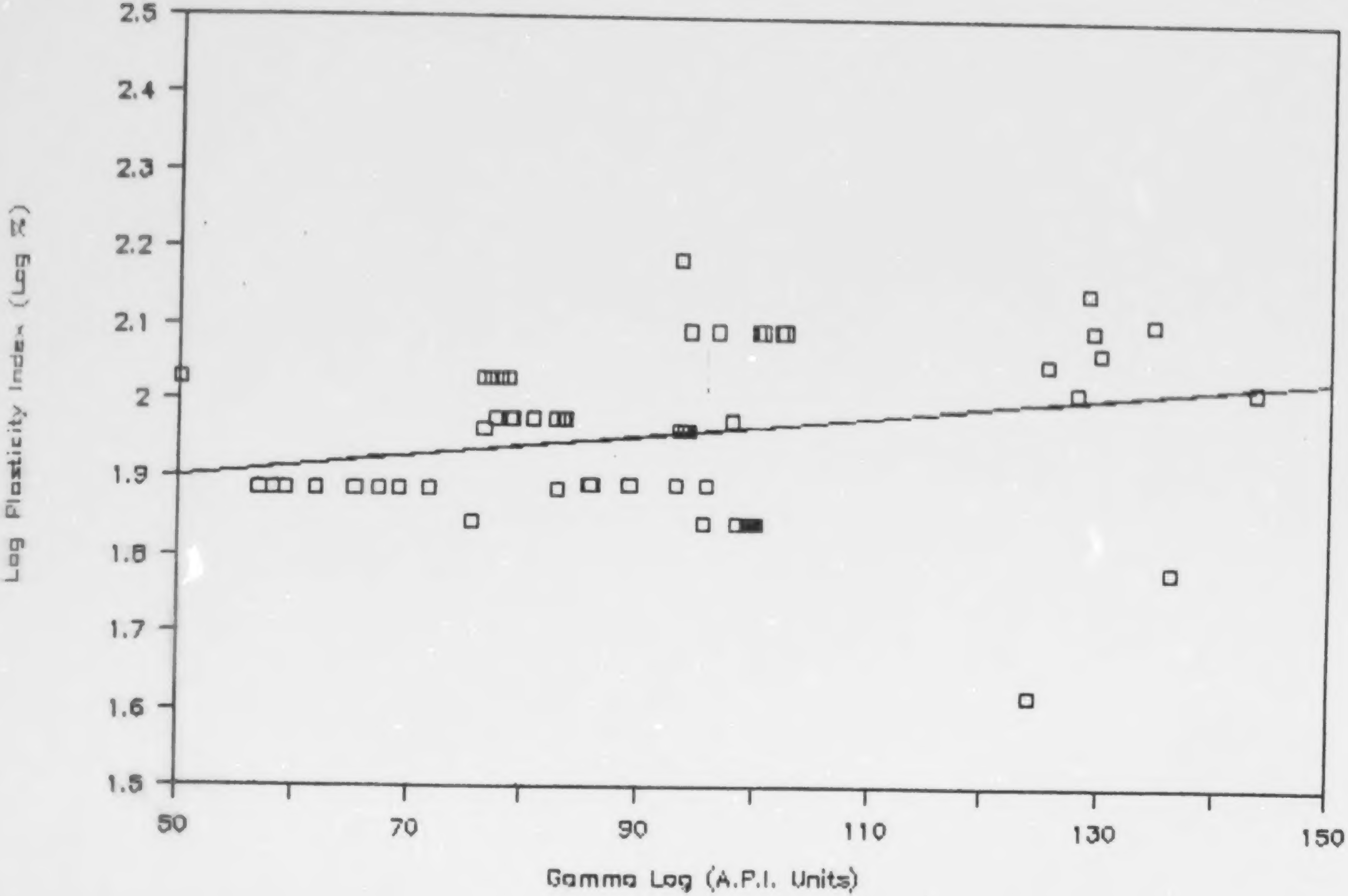
Log Kcw Plasticity Index vs Gamma Log



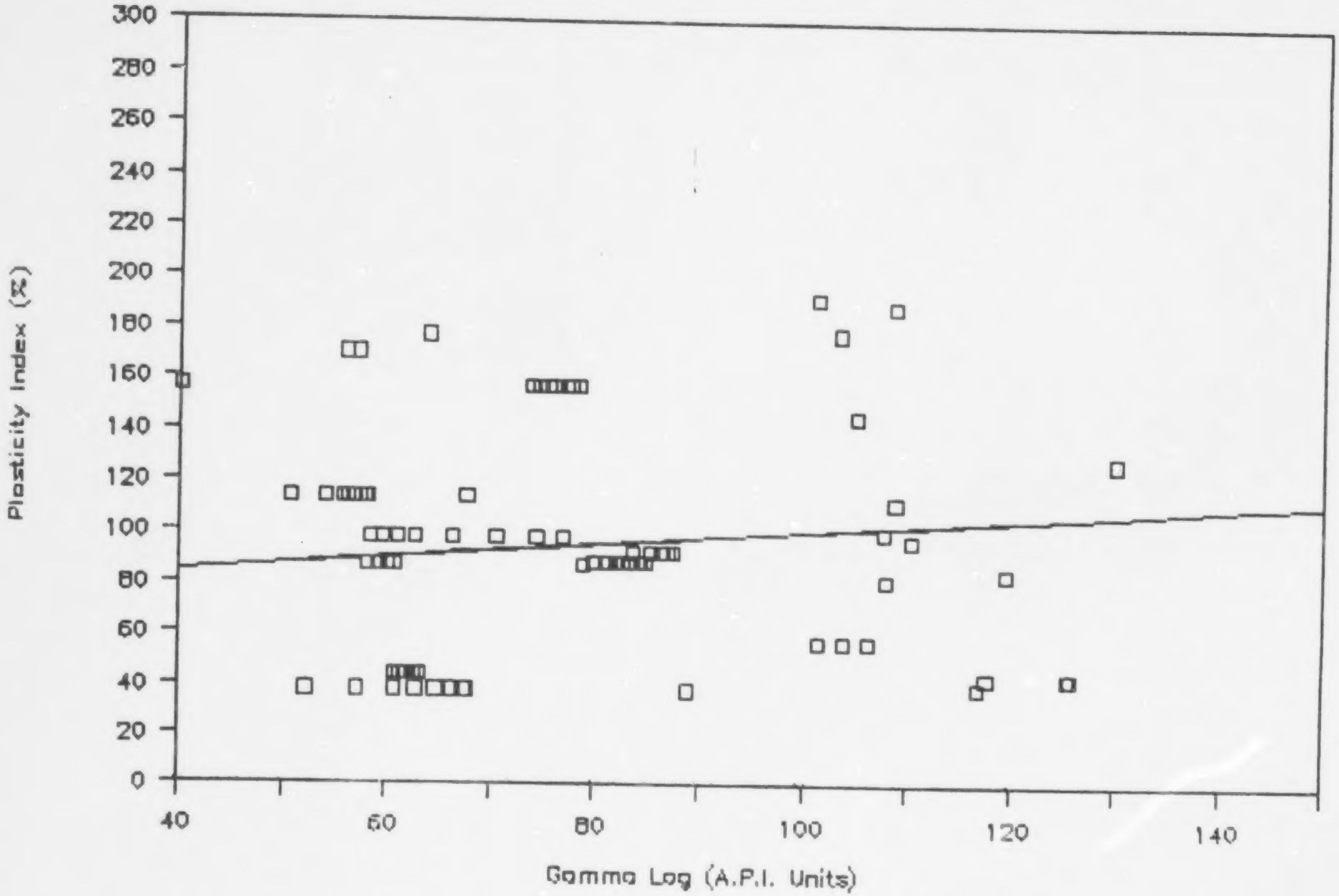
Kca Plasticity Index vs Gamma Log

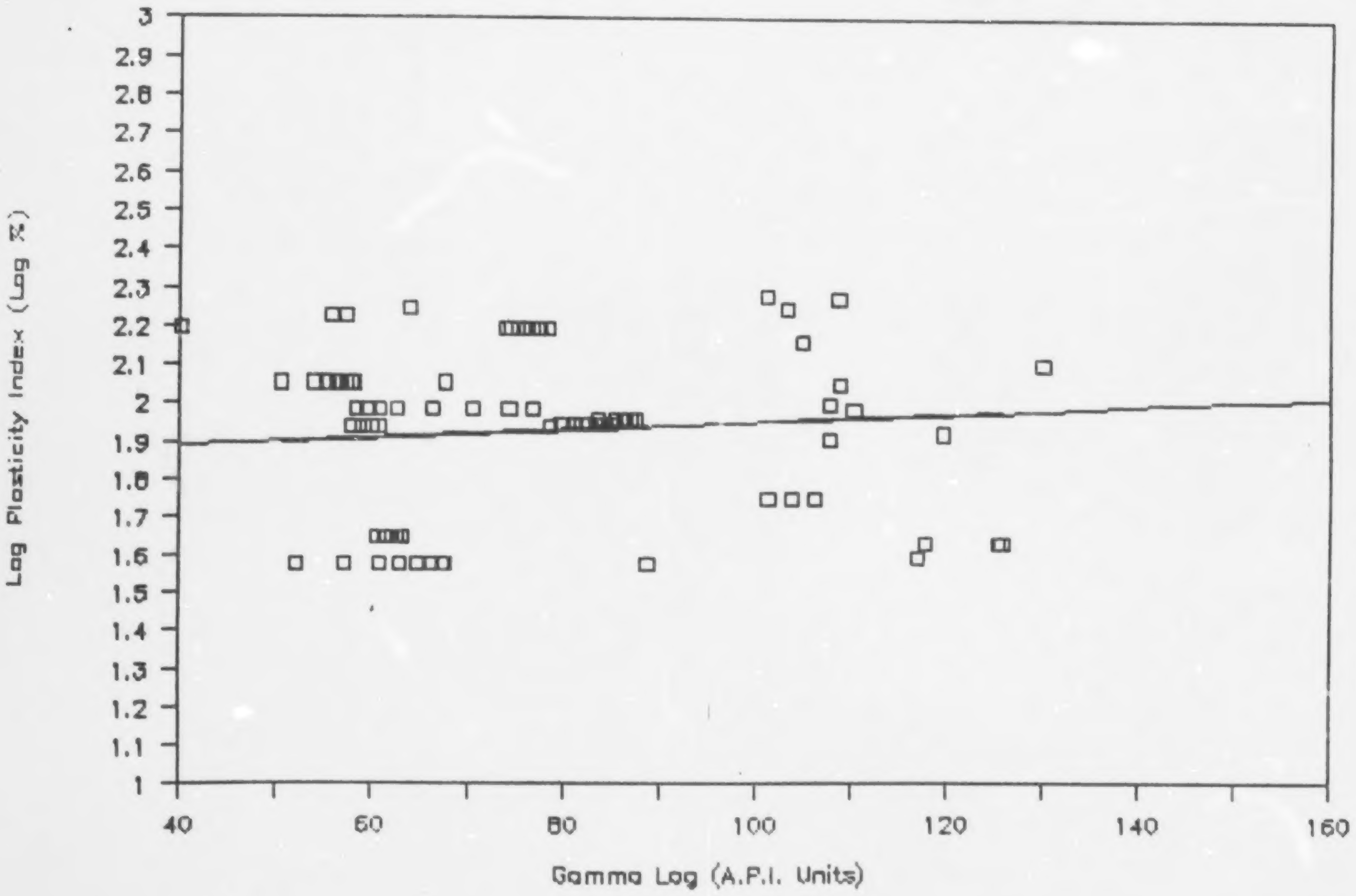


Log Kca Plasticity Index vs Gamma Log



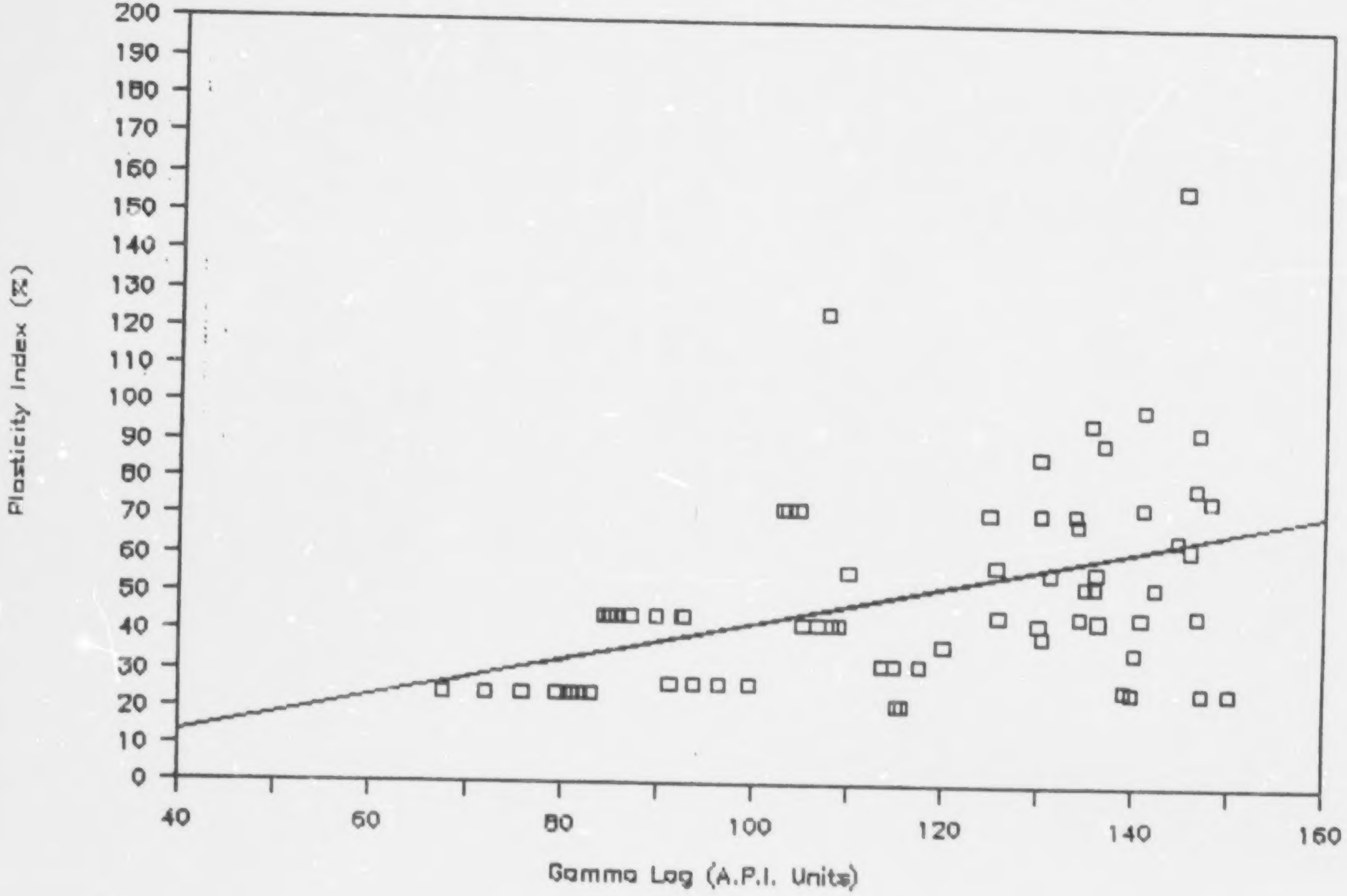
Kcb Plasticity Index vs Gamma Log



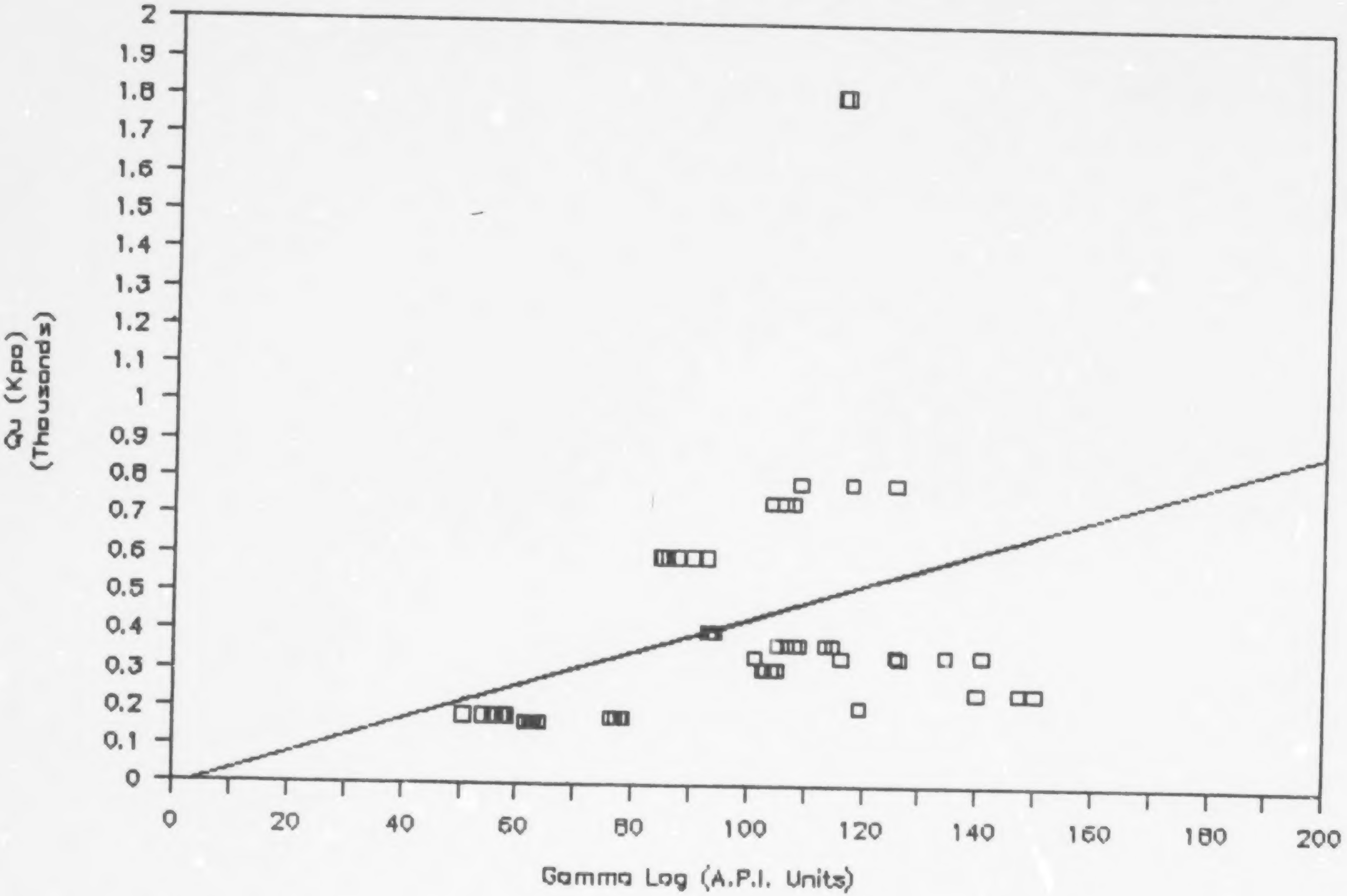


Log Kcb Plasticity Index vs Gamma Log

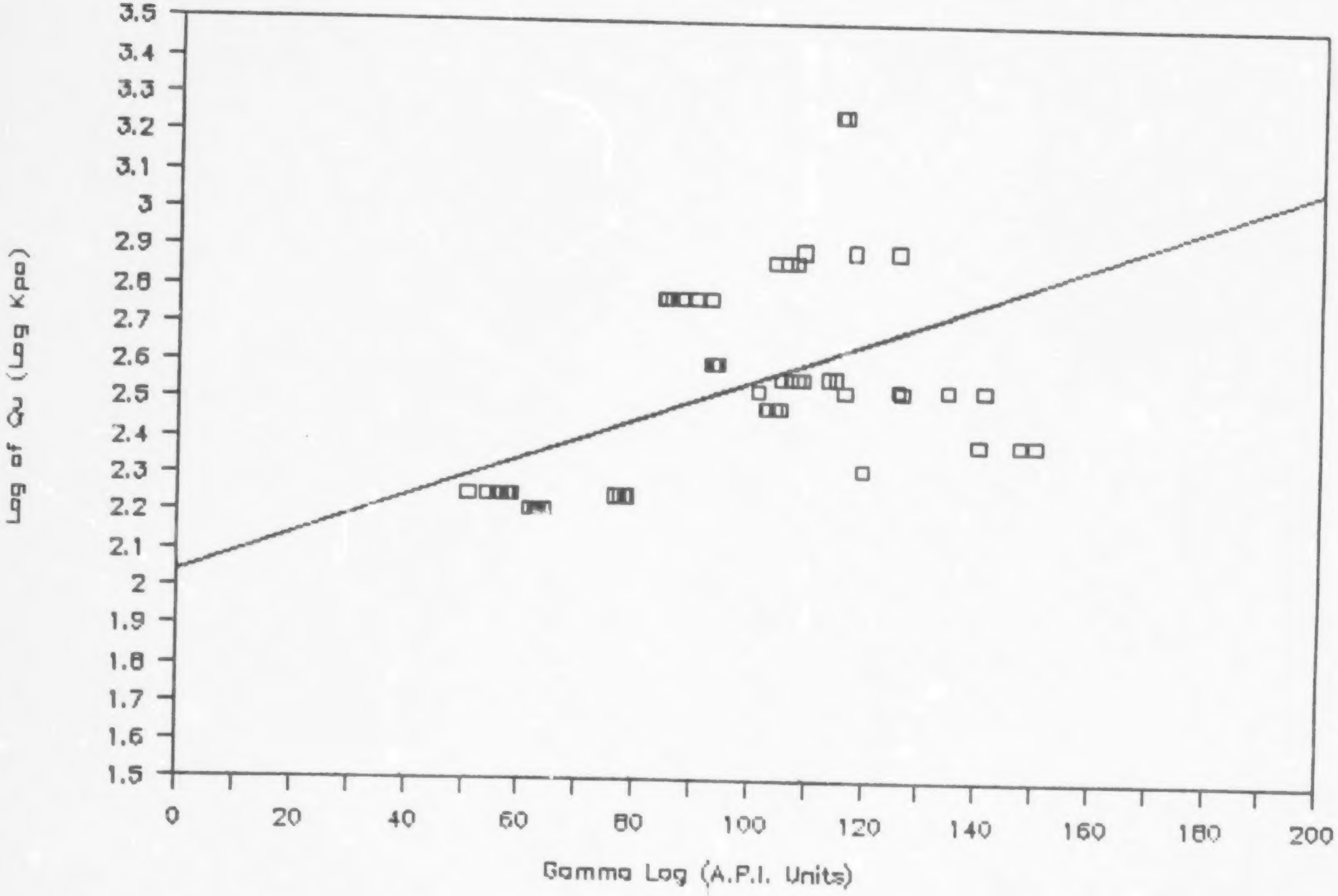
Kcc Plasticity Index vs Gamma Log



Undrained Shear Strength.vs.Gamma Log



Log of Shear Strength vs Gamma Log



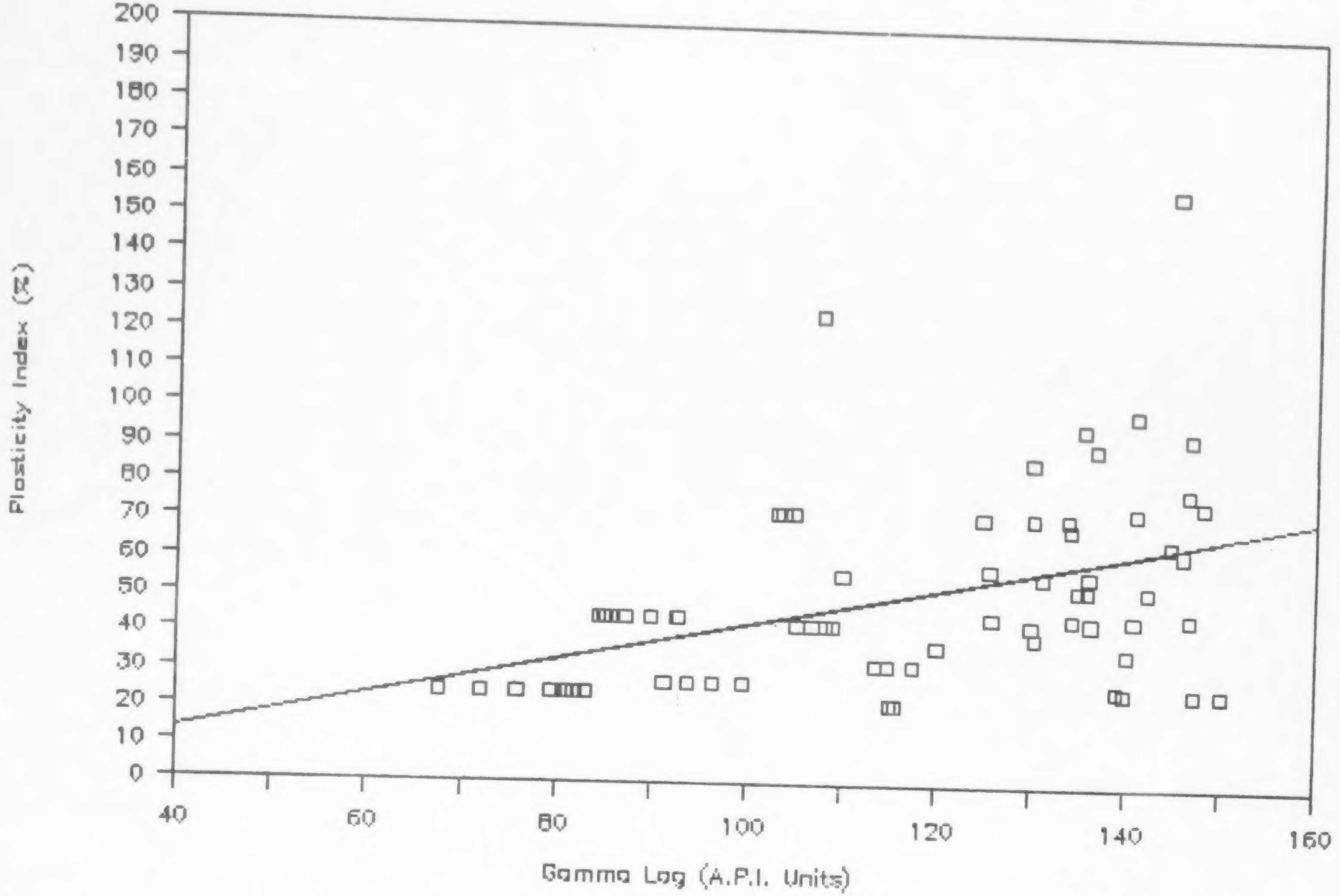
Regression Output for Plastic Index vs Bulk Density Log

```
         Regression Output:
Constant                    399.2752
Std Err of Y Est            31.76982
R Squared                   0.191360          R Value  0.437447
No. of Observations              162
Degrees of Freedom               160

X Coefficient(s)  -157.076
Std Err of Coef.  25.52718                    Y=-157.076*X+399.2752
```

Regression Analysis Output for
        Log of Plasticity Index vs Bulk Density Log

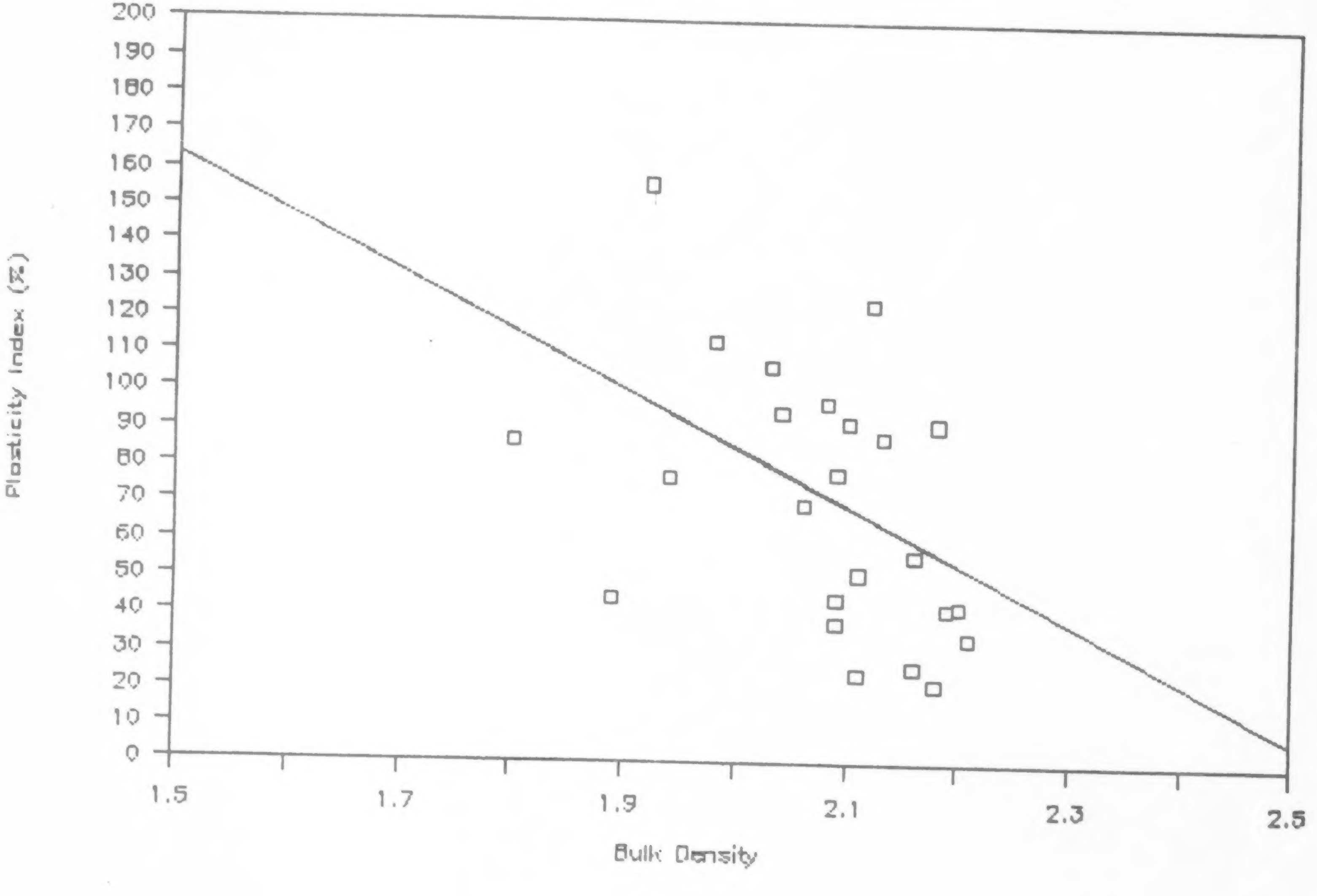
```
         Regression Output:
Constant                    3.966550
Std Err of Y Est            0.212613
R Squared                   0.188164          R Value  0.433778
No. of Observations              162
Degrees of Freedom               160

X Coefficient(s)  -1.04033
Std Err of Coef.  0.170835                    Y=-1.040*X+3.967
```

Kcc Plasticity Index vs Gamma Log

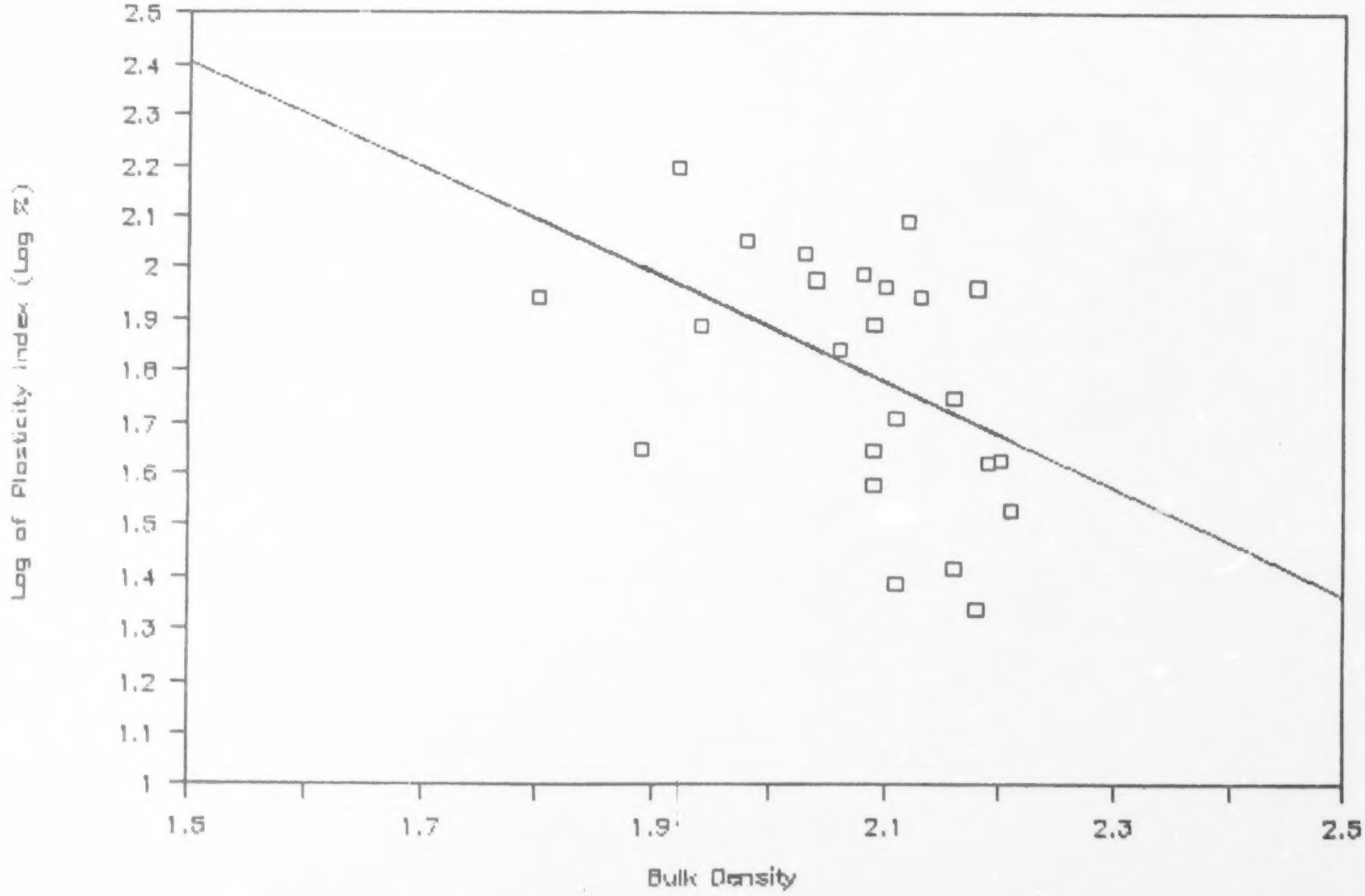


```
Regression Analysis Output for
        Undrained Shear Strength vs Gamma Log


        Regression Output:
Constant                        -13.7223
Std Err of Y Est                304.7697
R Squared                       0.133160          R Value      0.365
No. of Observations                   61
Degrees of Freedom                    59

X Coefficient(s)  4.524302
Std Err of Coef.  1.502821                        Y=4.524*X-13.722


Regression Output for
        Log of Undrained Shear Strength vs Gamma Log


        Regression Output:
Constant                        2.038909
Std Err of Y Est                0.227086
R Squared                       0.266240          R Value  0.515984
No. of Observations                   61
Degrees of Freedom                    59

X Coefficient(s)  0.005180
Std Err of Coef.  0.001119                        Y=0.005*X+2.039
```

Plasticity Index vs Bulk Density Log



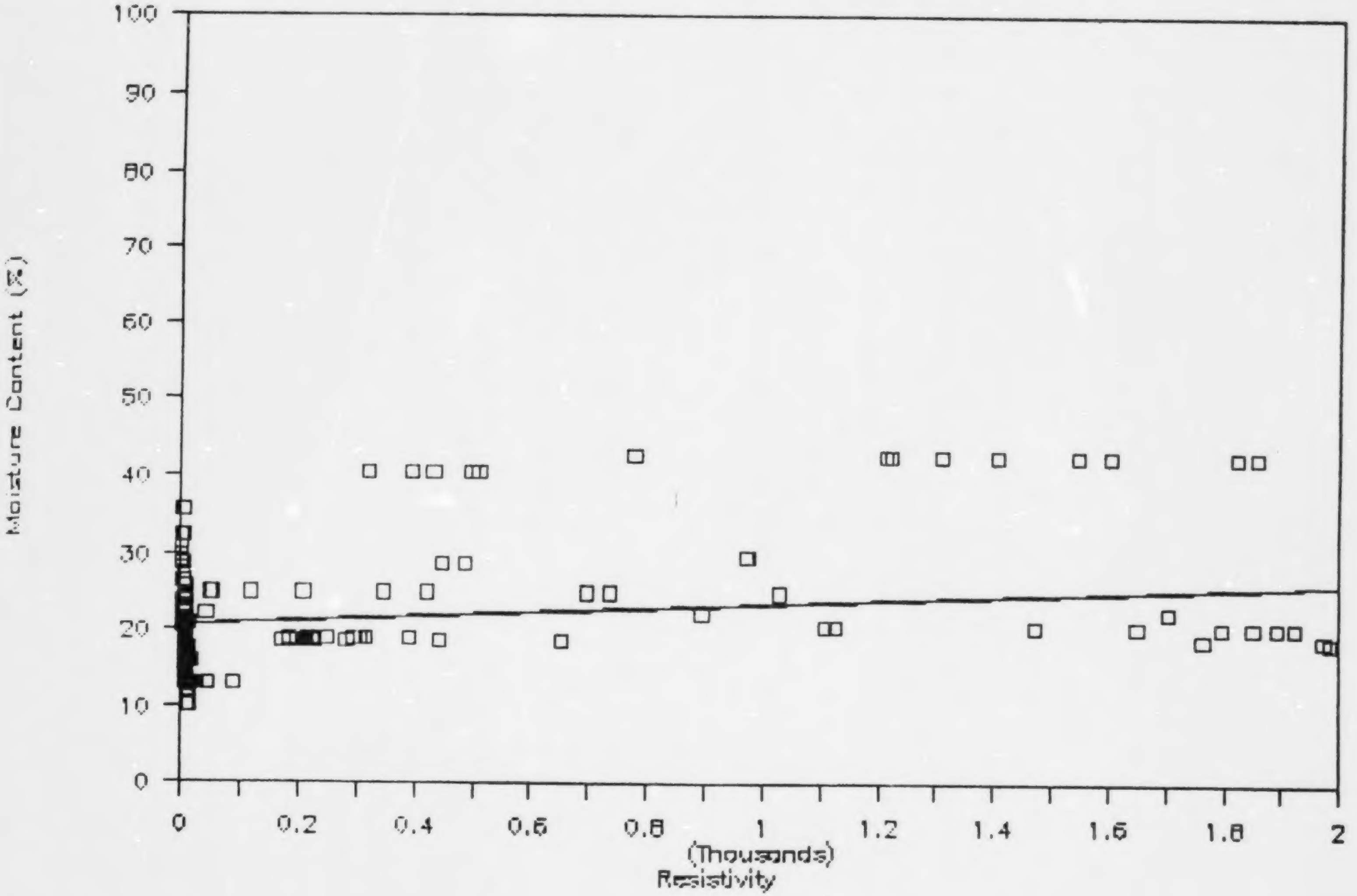
Log Plastic Index vs Bulk Density Log



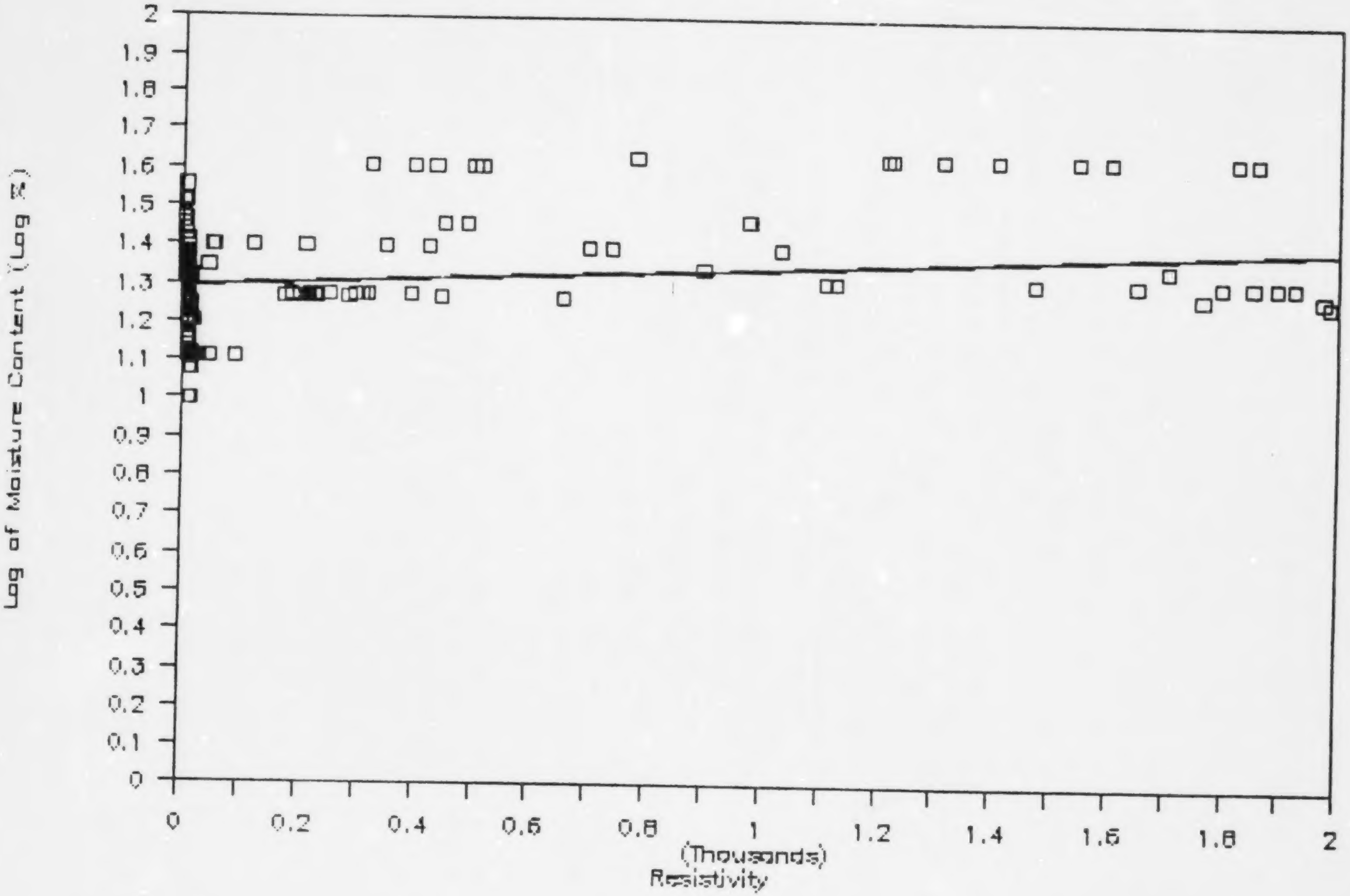
```
Regression Analysis Output for
        Moisture Content (%) vs Resistivity Log


        Regression Output:
Constant                           20.616
Std Err of Y Est                    7.191
R Squared                           0.065      R Value     0.254
No. of Observations               238.000
Degrees of Freedom                236.000

X Coefficient(s)      0.003
Std Err of Coef.      0.001                    Y=0.003*X+20.616
```

```
Regression Analysis Output for
        Log of Moisture Content (Log%) vs Resistivity Log


        Regression Output:
Constant                            1.293
Std Err of Y Est                    0.134
R Squared                           0.067      R Value     0.259
No. of Observations               238.000
Degrees of Freedom                236.000

X Coefficient(s)  5.50E-05
Std Err of Coef.  1.33E-05                     Y=5.50E-05*X+1.293
```

Moisture Content (%) vs Resistivity Log



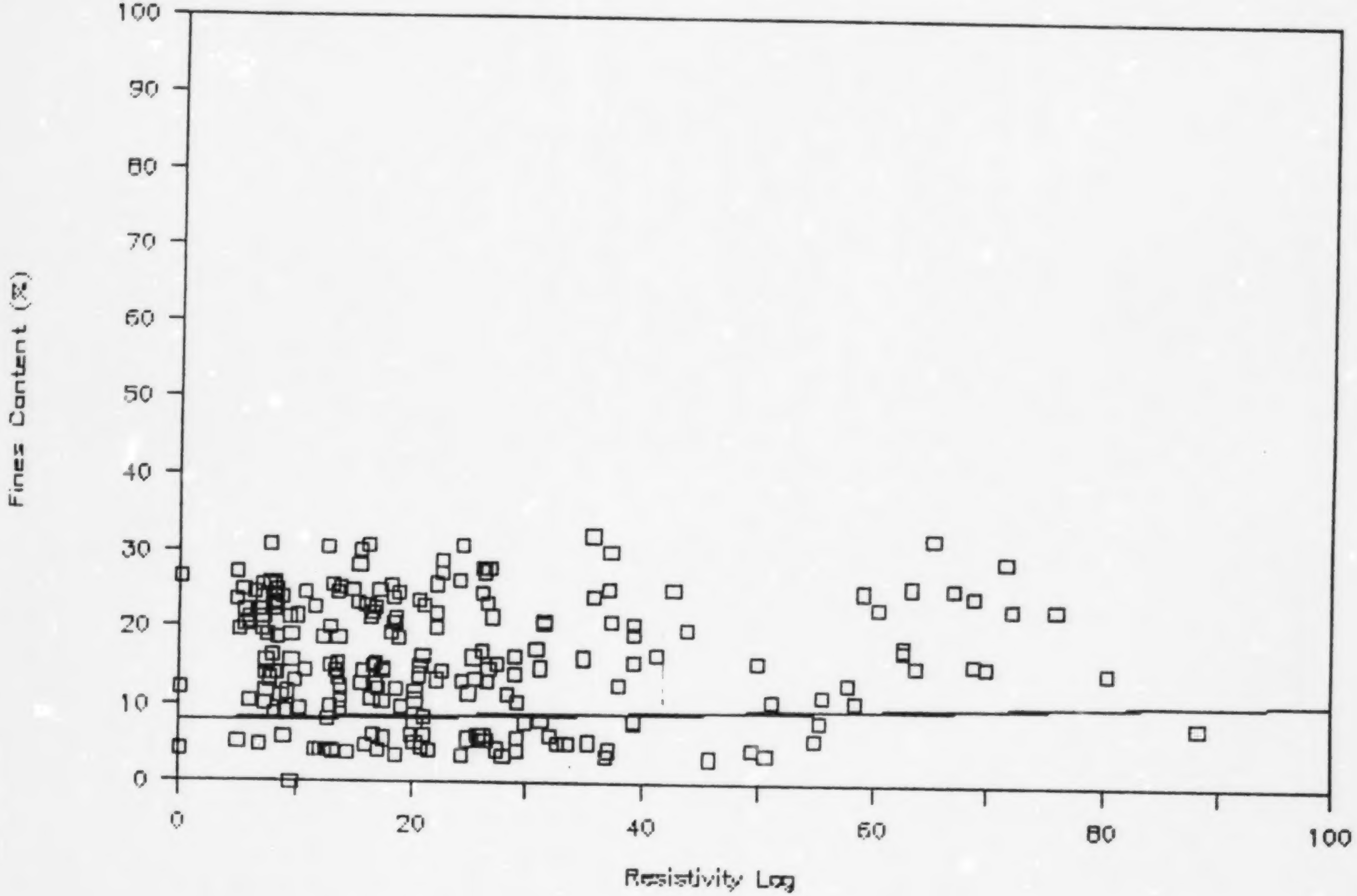
Moisture Content vs Resistivity Log

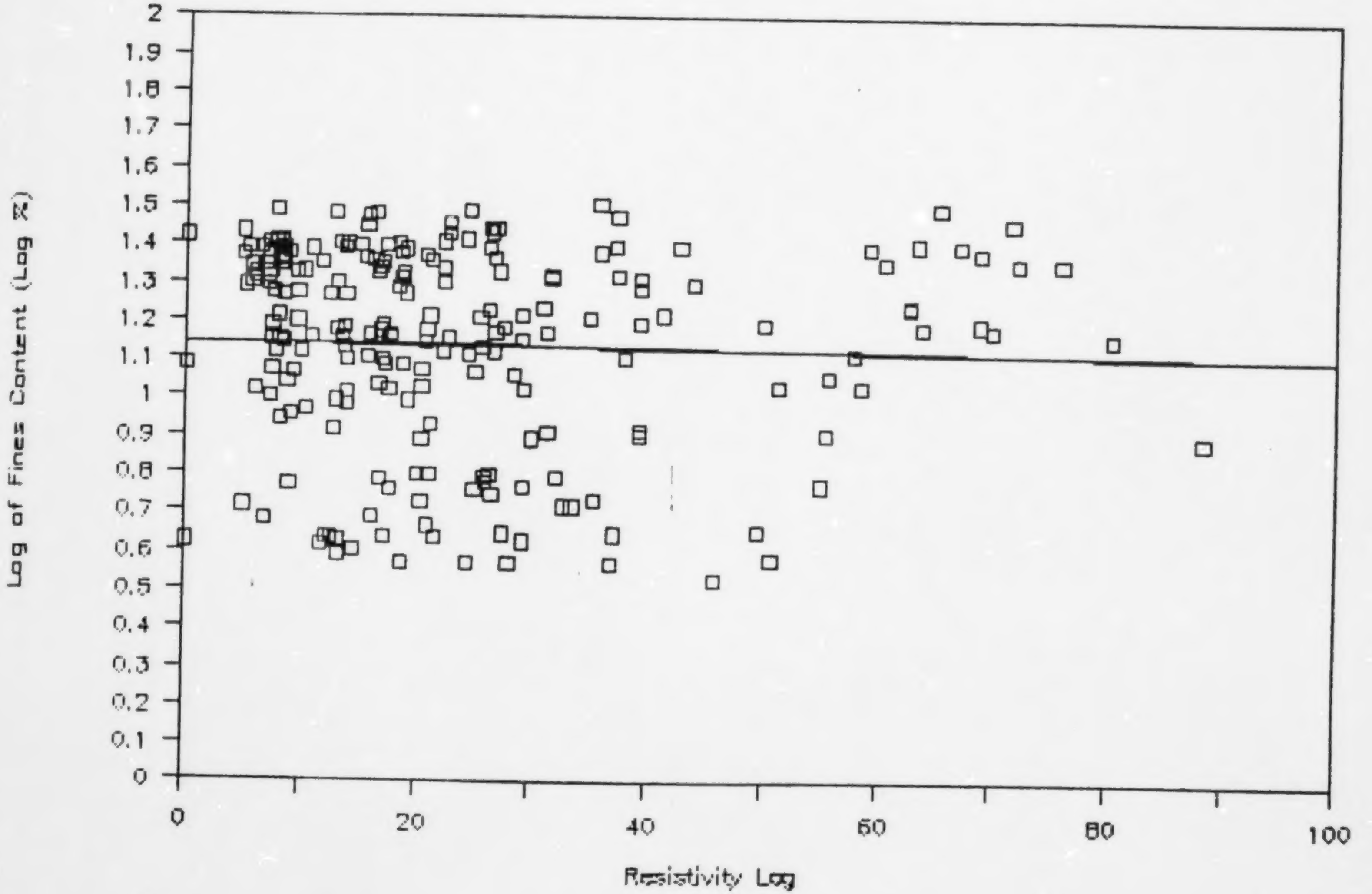


```
Regression Analysis Output for
        Fines Content (%) vs Resistivity Log


        Regression Output:
Constant                          16.330
Std Err of Y Est                   7.879
R Squared                          0.001          R Value      0.024
No. of Observations              219.000
Degrees of Freedom               217.000

X Coefficient(s)    -0.011
Std Err of Coef.     0.031                        Y=-0.011*X+16.330
```

```
Regression Analysis Output for
        Log of Fines Content (Log %) vs Resistivity Log


        Regression Output:
Constant                           1.143
Std Err of Y Est                   0.275
R Squared                        0.00039          R Value      0.020
No. of Observations              219.000
Degrees of Freedom               217.000

X Coefficient(s)  -0.00031
Std Err of Coef.     0.001                        Y=-0.0003*X+1.143
```

Fines Content (%) vs Resistivity Log





Fine Content (Log%) vs Resistivity Log

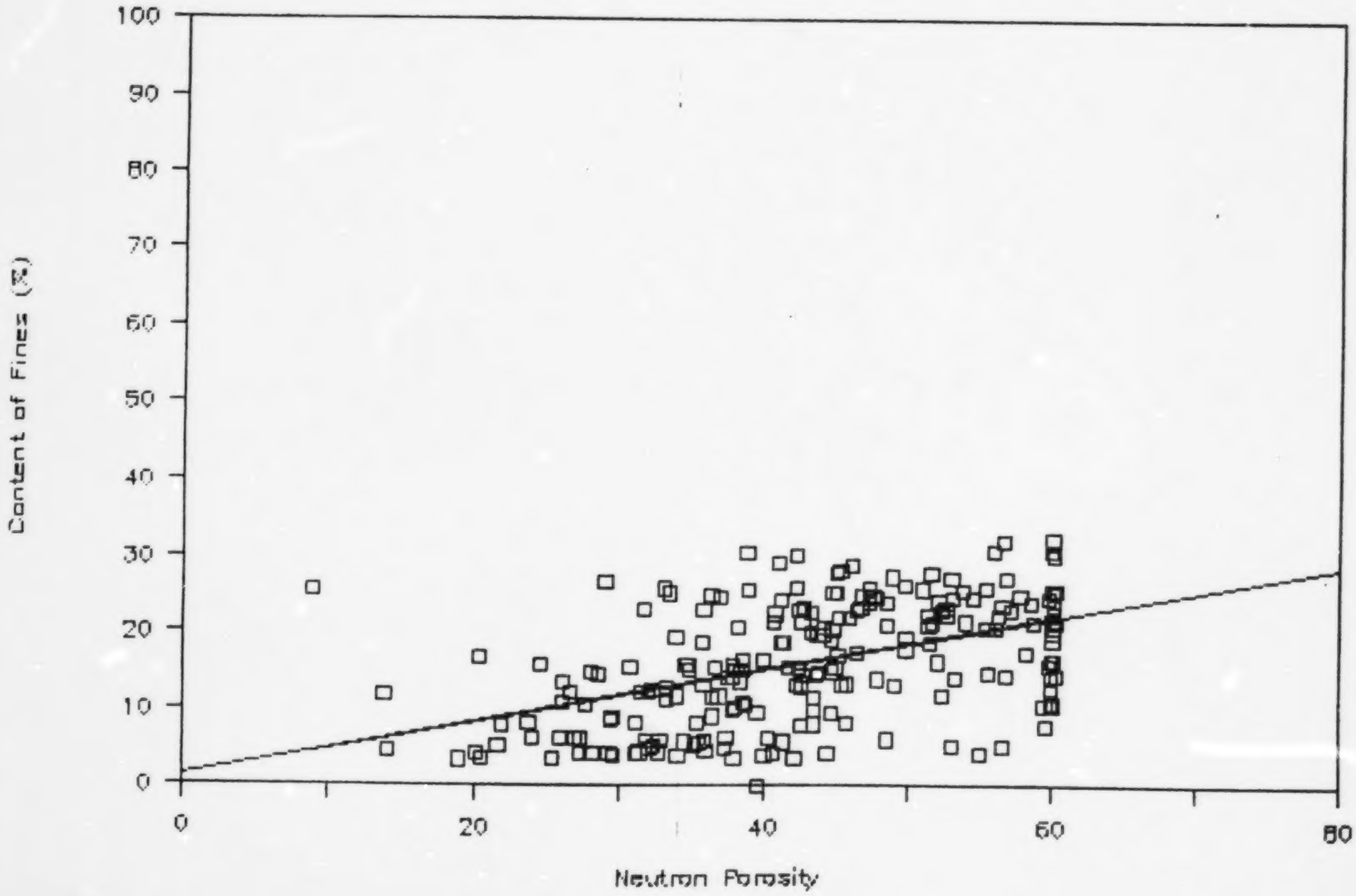
Regression Analysis Output for
Fines Content (%) vs Neutron Porosity Log

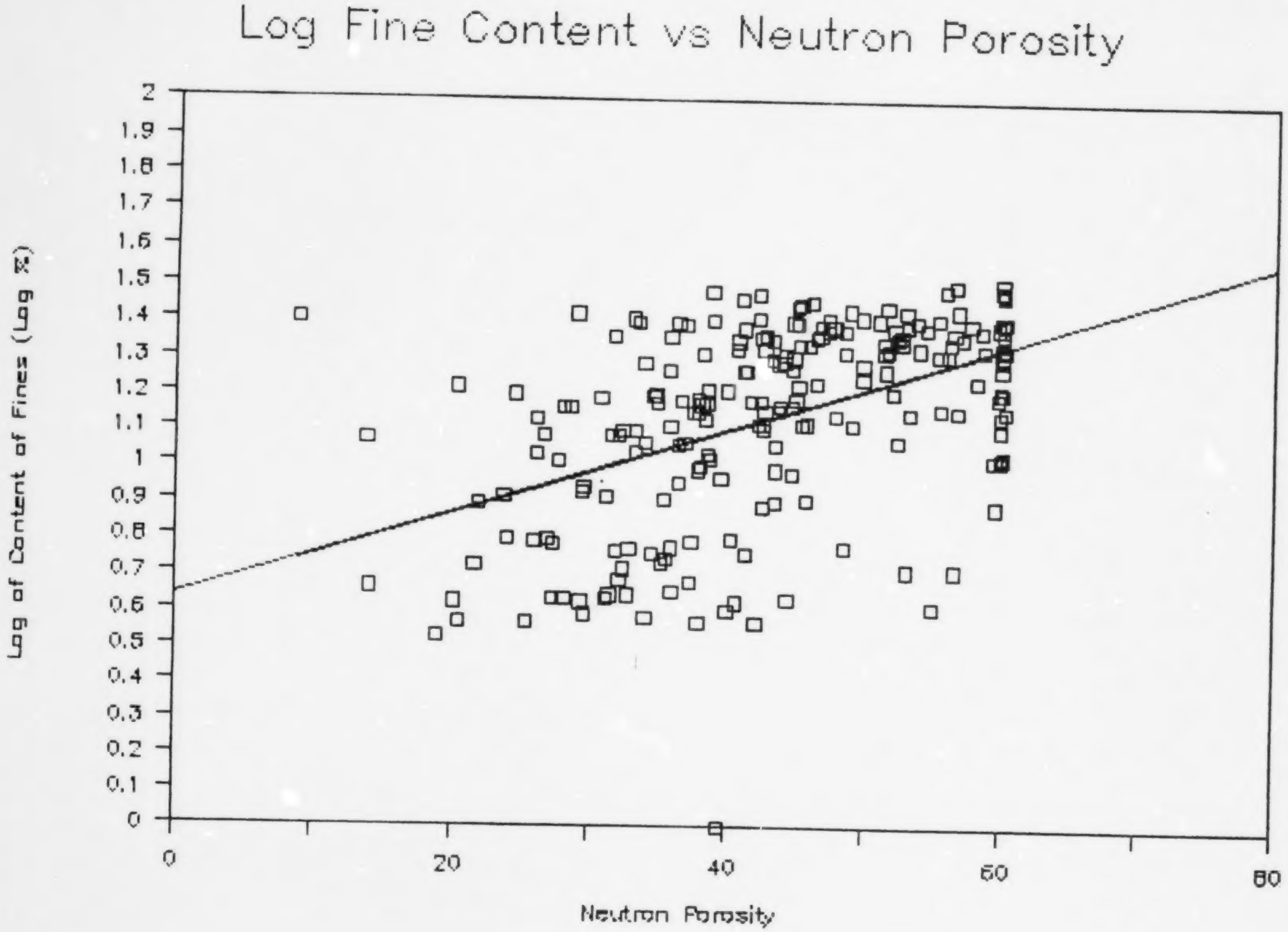
```
        Regression Output:
Constant                      1.481
Std Err of Y Est              6.878
R Squared                     0.238          R Value   0.48832
No. of Observations         219.000
Degrees of Freedom          217.000

X Coefficient(s)      0.340
Std Err of Coef.      0.041                  Y=0.340*X+1.418
```

Regression Analysis Output for
Log of Fines Content (Log %) vs Neutron Porosity Log

```
        Regression Output:
Constant                      0.634
Std Err of Y Est              0.241
R Squared                     0.232          R Value   0.49068
No. of Observations         219.000
Degrees of Freedom          217.000

X Coefficient(s)      0.012
Std Err of Coef.      0.001                  Y=0.012*X+0.634
```

Fine Content(%) vs Neutron Porosity Log



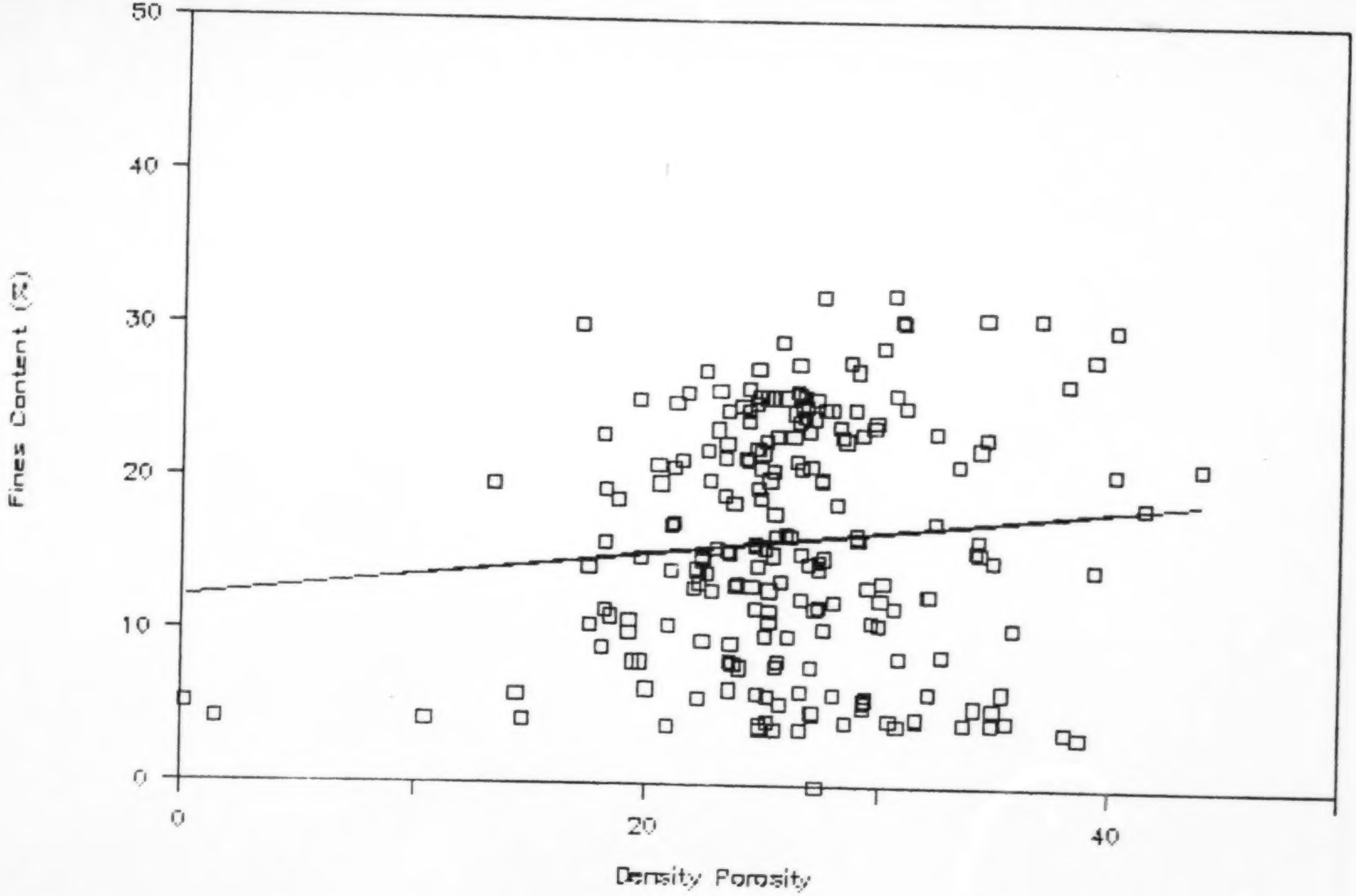


Log Fine Content vs Neutron Porosity

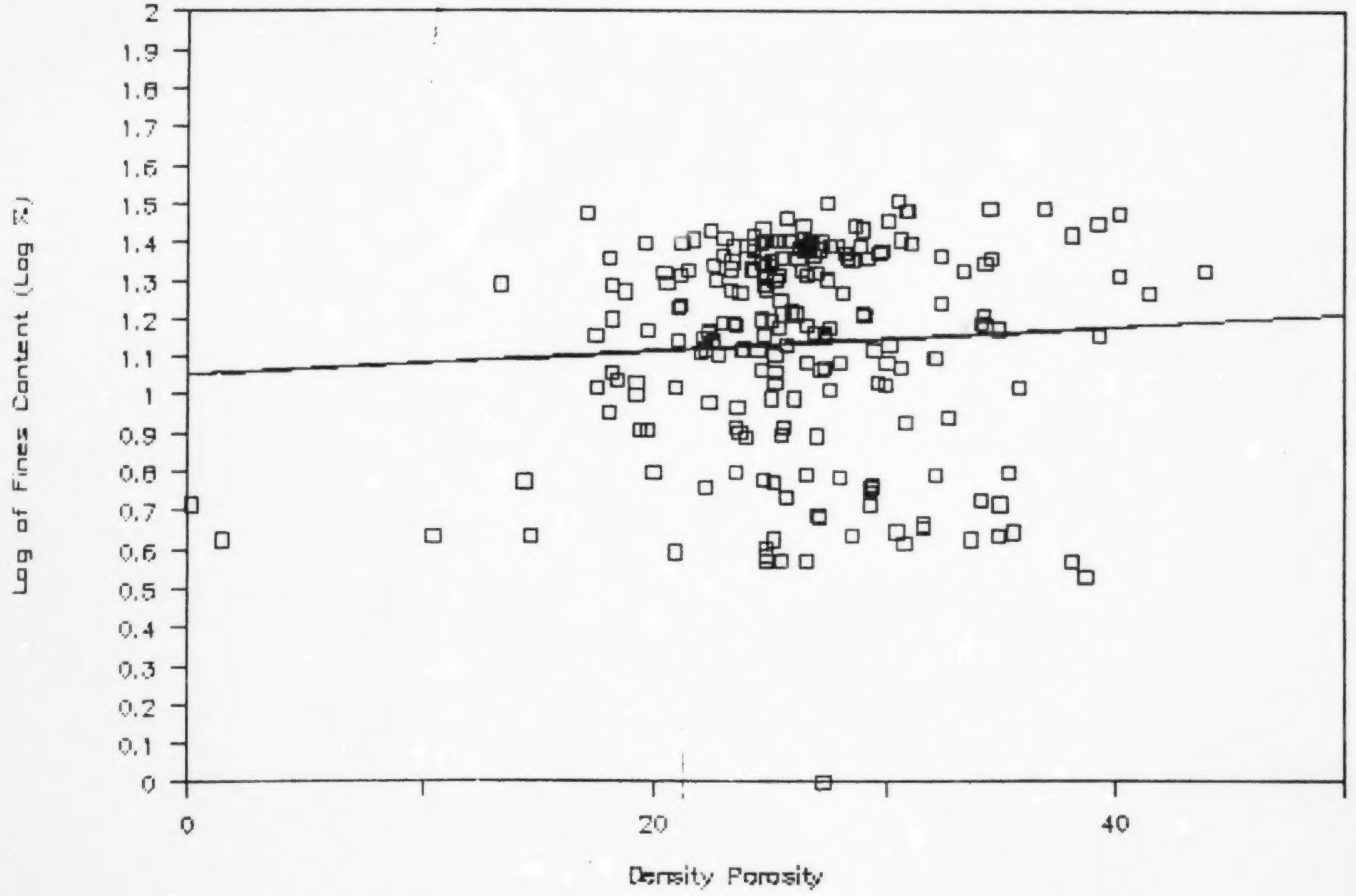
```
Regression Analysis Output for
       Fines Content (%) vs Density Porosity


       Regression Output:
Constant                     12.159
Std Err of Y Est              7.834
R Squared                     0.012        R Value     0.110
No. of Observations         219.000
Degrees of Freedom          217.000

X Coefficient(s)    0.149
Std Err of Coef.    0.092                  Y=0.149*X+12.159
```

```
Regression Analysis Output for
       Log of Fines Content (Log %) vs Density Porosity


       Regression Output:
Constant                      1.053
Std Err of Y Est              0.274
R Squared                     0.004        R Value     0.067
No. of Observations         219.000
Degrees of Freedom          217.000

X Coefficient(s)    0.003
Std Err of Coef.    0.003                  Y=0.003*X+1.053
```

Fines Content (%) vs Density Porosity



Log Fines Content vs Density Porosity



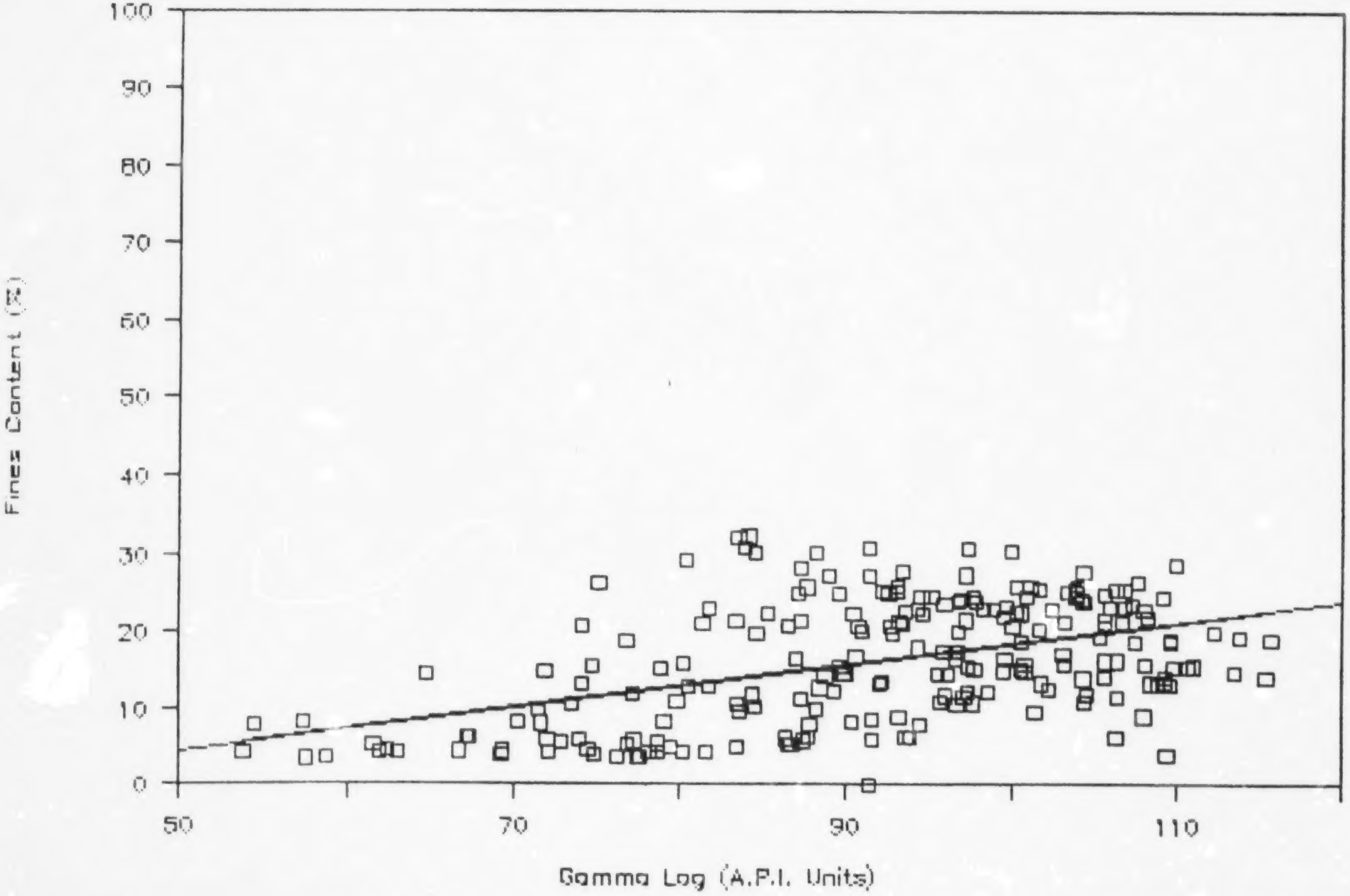
Regression Analysis Output for Fines Content (%) vs Gamma Log

```
         Regression Output:
Constant                      -9.296
Std Err of Y Est               6.946
R Squared                      0.223        R Value      0.472
No. of Observations          219.000
Degrees of Freedom           217.000

X Coefficient(s)      0.276
Std Err of Coef.      0.035                 Y=0.276*X-9.296
```

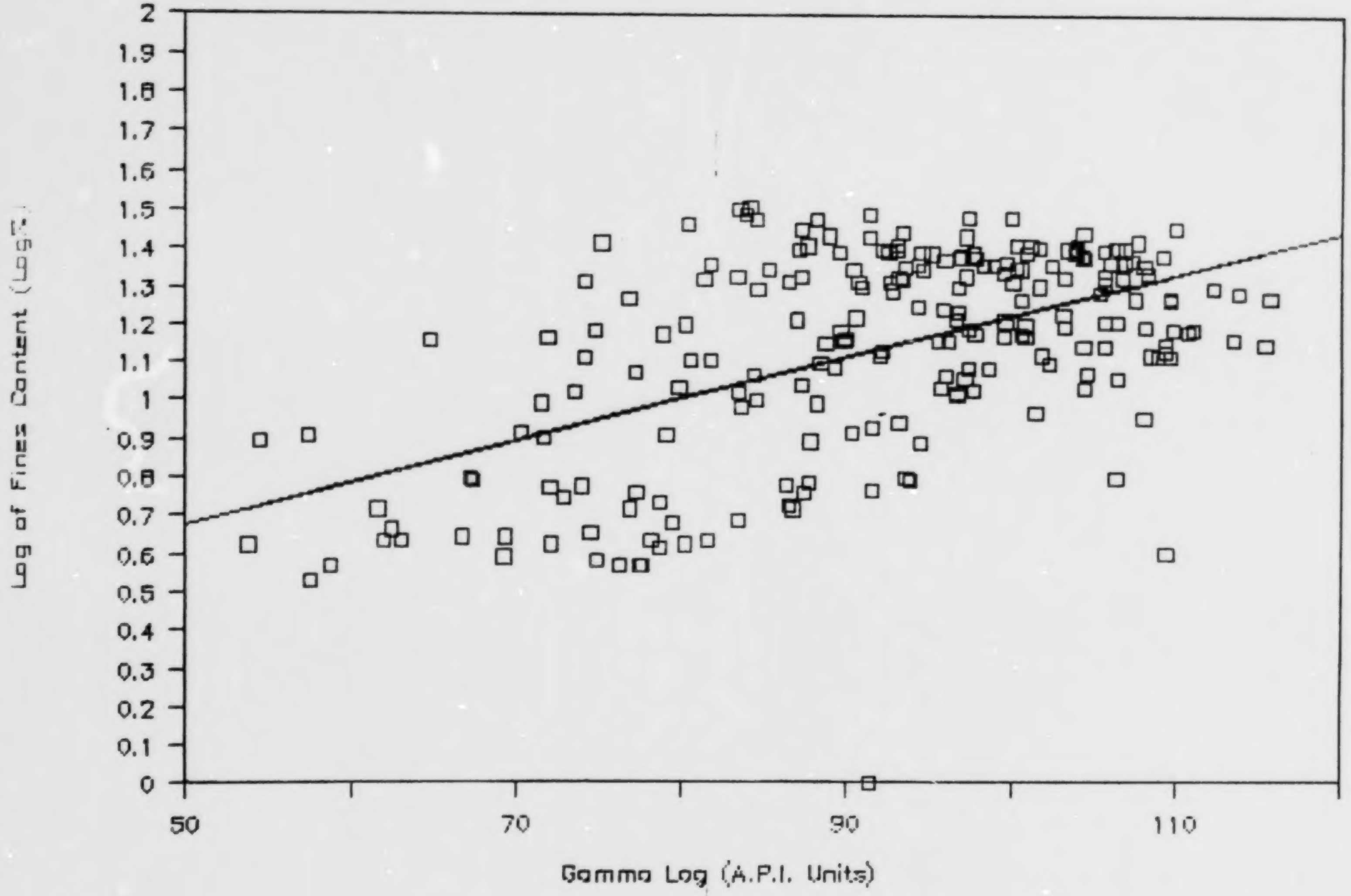
Regression Analysis Output for Log of Fines Content (Log %) vs Gamma Log

```
         Regression Output:
Constant                       0.125
Std Err of Y Est               0.231
R Squared                      0.292        R Value      0.540
No. of Observations          219.000
Degrees of Freedom           217.000

X Coefficient(s)      0.011
Std Err of Coef.      0.001                 Y=0.011*X+0.125
```

Fines Content (%) vs Gamma Log

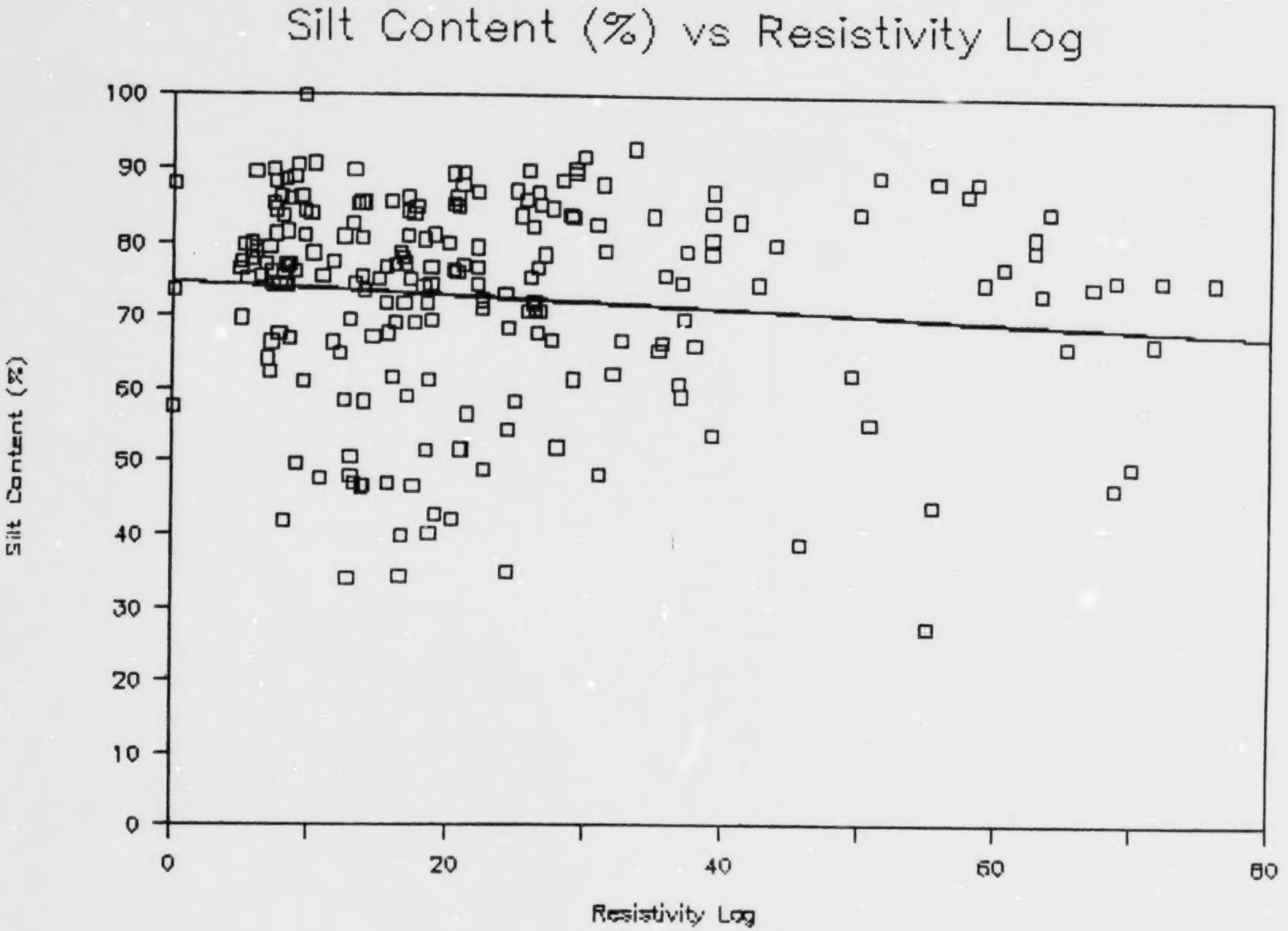


Log of Fines Content(Log%) vs Gamma Log



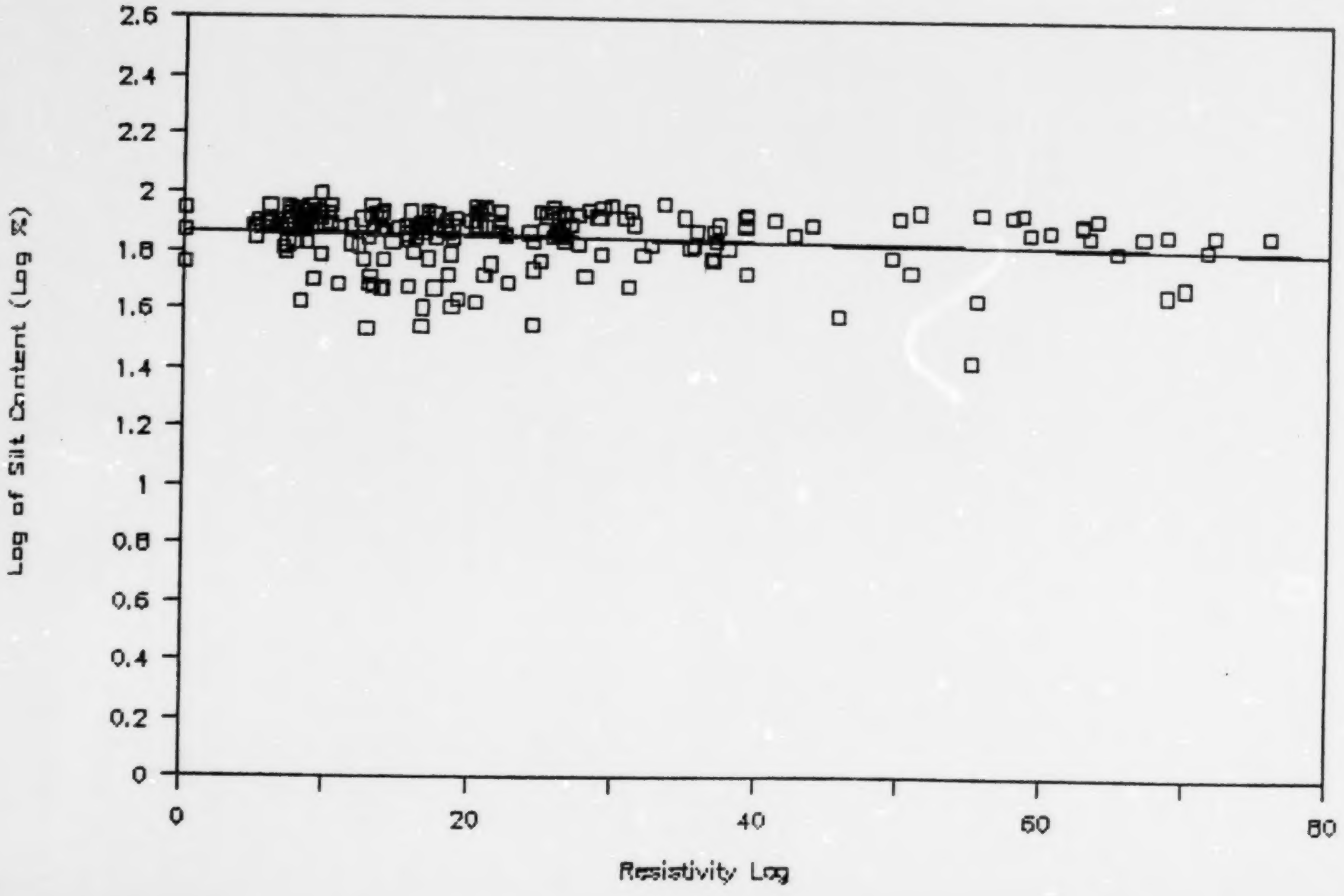
```
Regression Analysis Output for
        Silt Content (%) vs Resistivity Log


        Regression Output:
Constant                        74.774
Std Err of Y Est                13.967
R Squared                        0.012          R Value  0.109073
No. of Observations            219.000
Degrees of Freedom             217.000

X Coefficient(s)      -0.087
Std Err of Coef.       0.054                    Y=-0.087*X+74.744
```

```
Regression Analysis Output for
        Log of Fines Content (Log %) vs Resistivity Log


        Regression Output:
Constant                         1.867
Std Err of Y Est                 0.097
R Squared                        0.013          R Value     0.114
No. of Observations            219.000
Degrees of Freedom             217.000

X Coefficient(s)      -0.001
Std Err of Coef.       0.000                    Y=-0.001*X+1.867
```



Silt Content (%) vs Resistivity Log

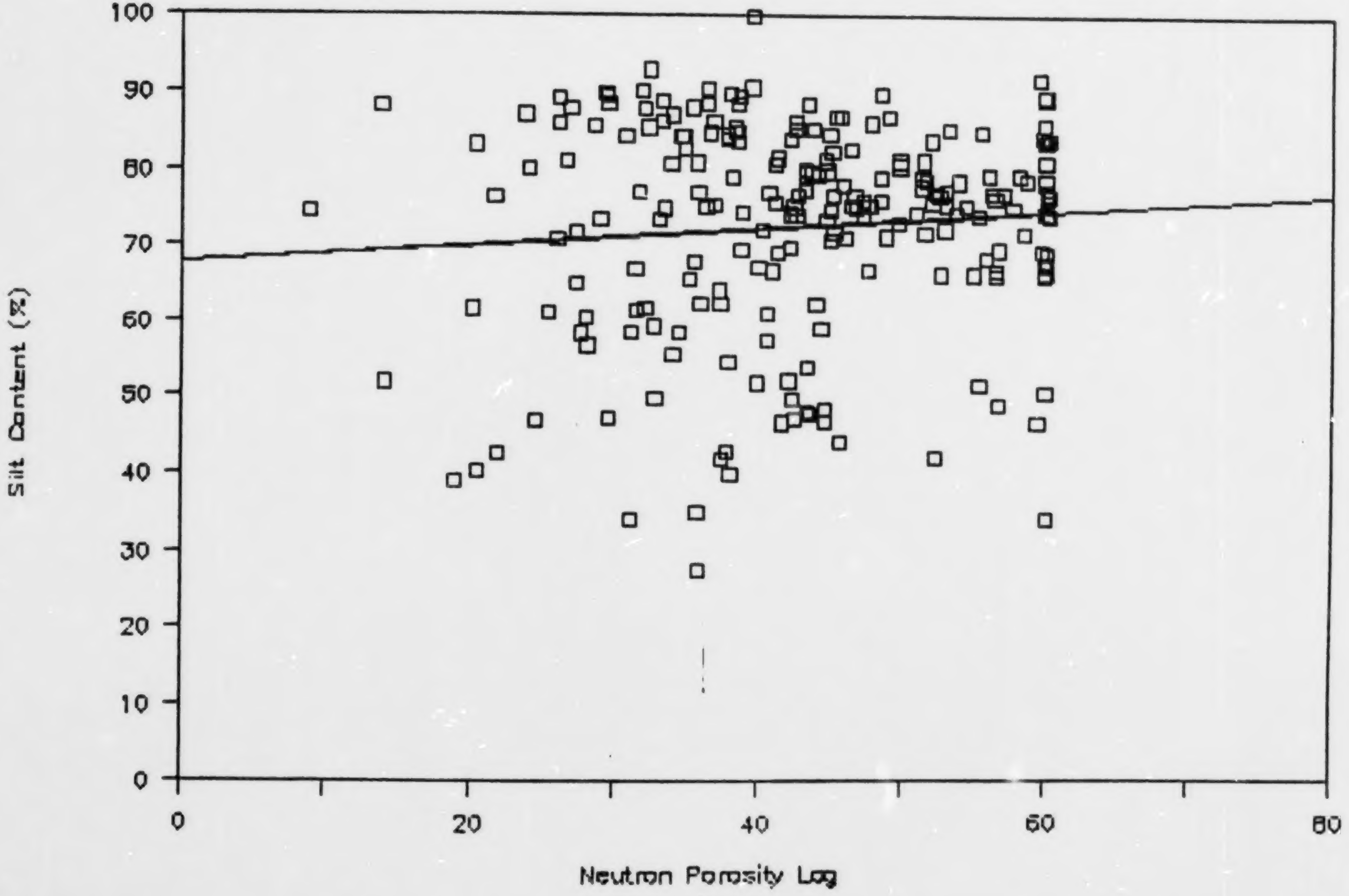
Log Silt Content (%) vs Resistivity Log

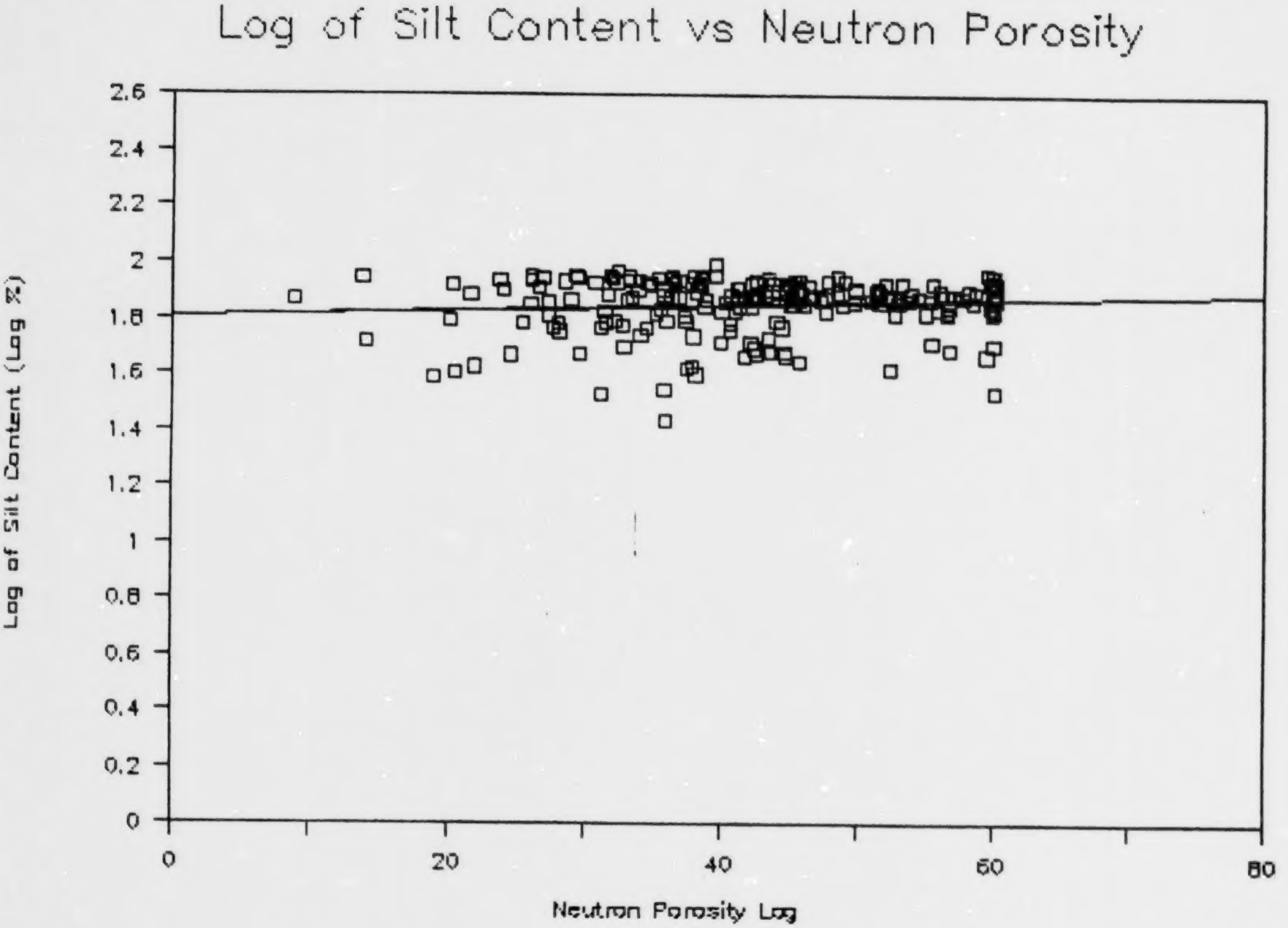


```
Regression Analysis Output for
        Silt Content (%) vs Neutron Porosity Log

        Regression Output:
Constant                        67.688
Std Err of Y Est                13.988
R Squared                        0.009        R Value     0.094
No. of Observations            219.000
Degrees of Freedom             217.000

X Coefficient(s)      0.117
Std Err of Coef.      0.084                   Y=0.117*X+67.688
```

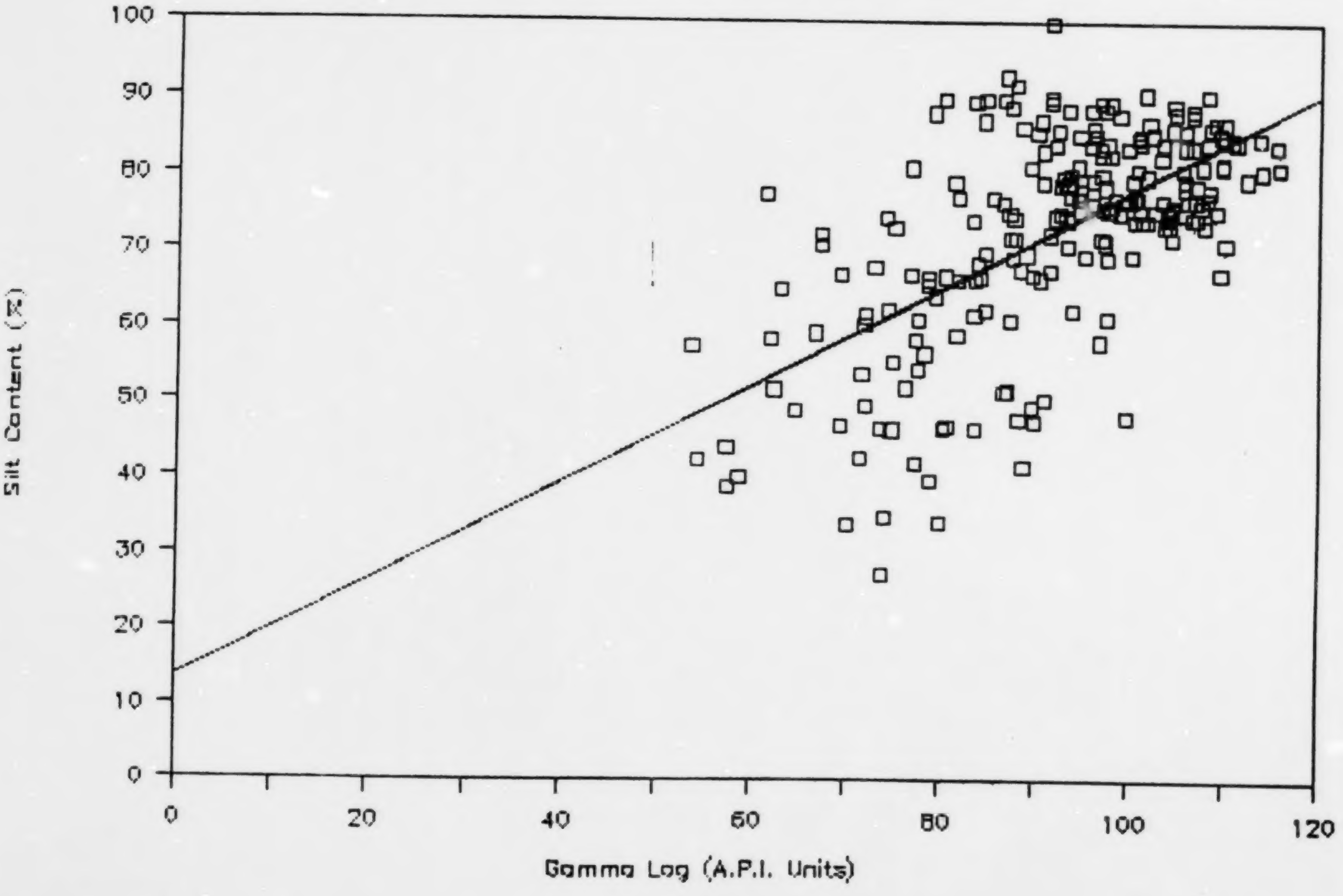
```
Regression Analysis Output for
        Log of Silt Content (Log %) vs Neutron Porosity Log

        Regression Output:
Constant                         1.808
Std Err of Y Est                 0.097
R Squared                        0.014        R Value     0.117
No. of Observations            219.000
Degrees of Freedom             217.000

X Coefficient(s)      0.001
Std Err of Coef.      0.001                   Y=0.001*X+1.808
```

Silt Content (%) vs Neutron Porosity

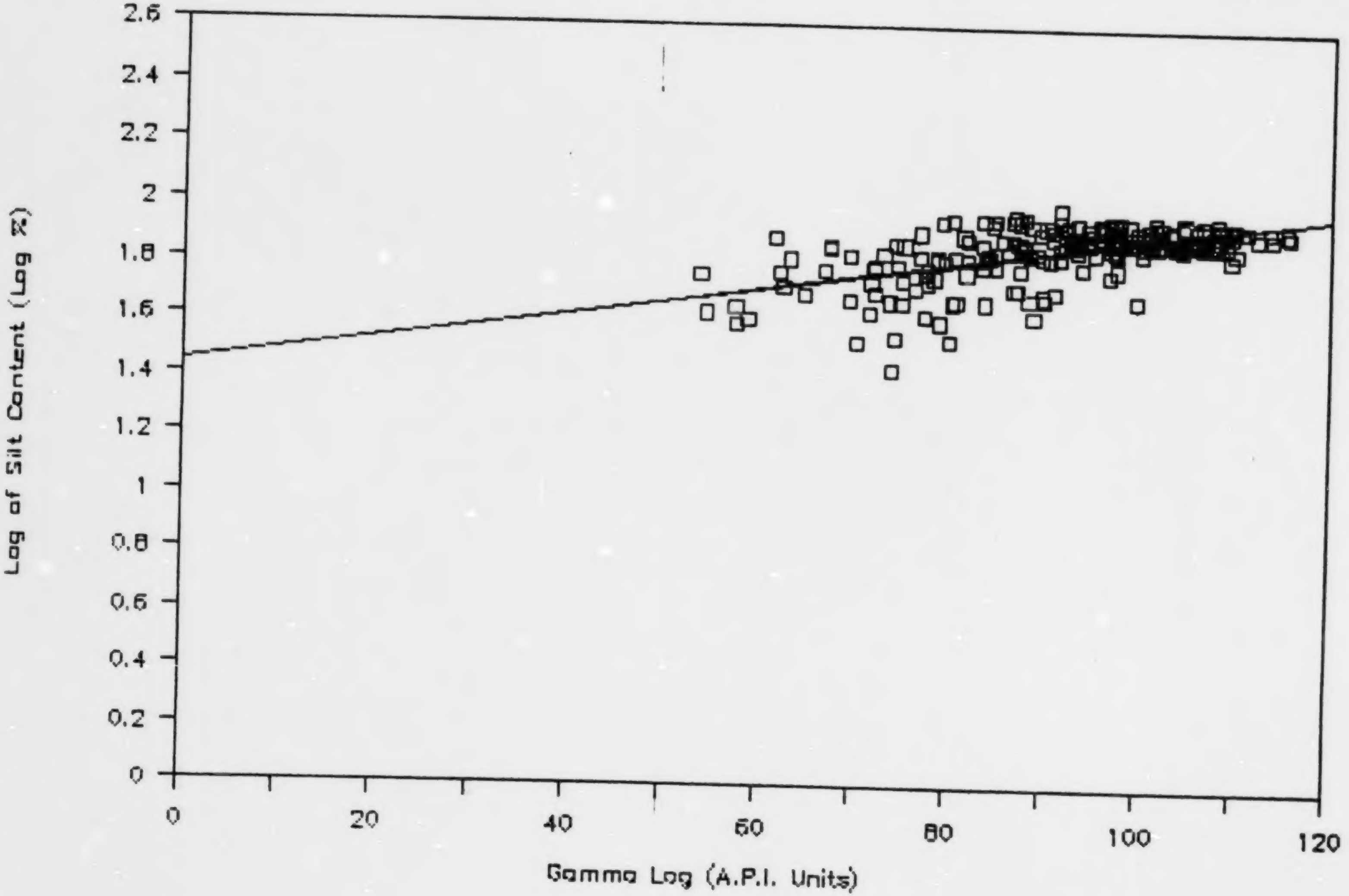



Log of Silt Content vs Neutron Porosity
Log of Silt Content (Log %)
2.6
2.4
2.2
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
20
40
60
80
Neutron Porosity Log

Silt Content (%) vs Gamma Log



Log of Silt Content(Log %) vs Gamma Log



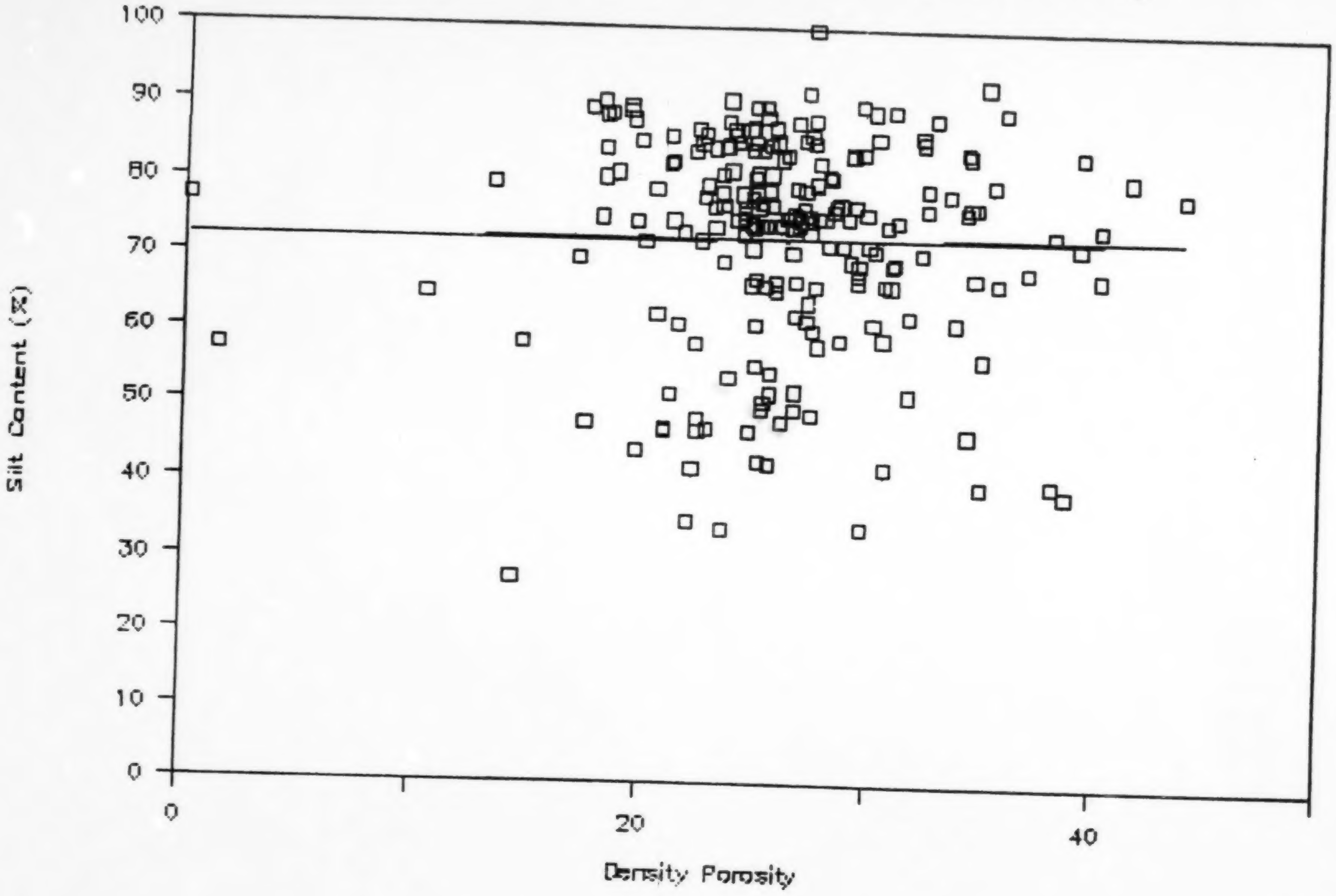
Regression Analysis Output for
Silt Content (%) vs Density Porosity

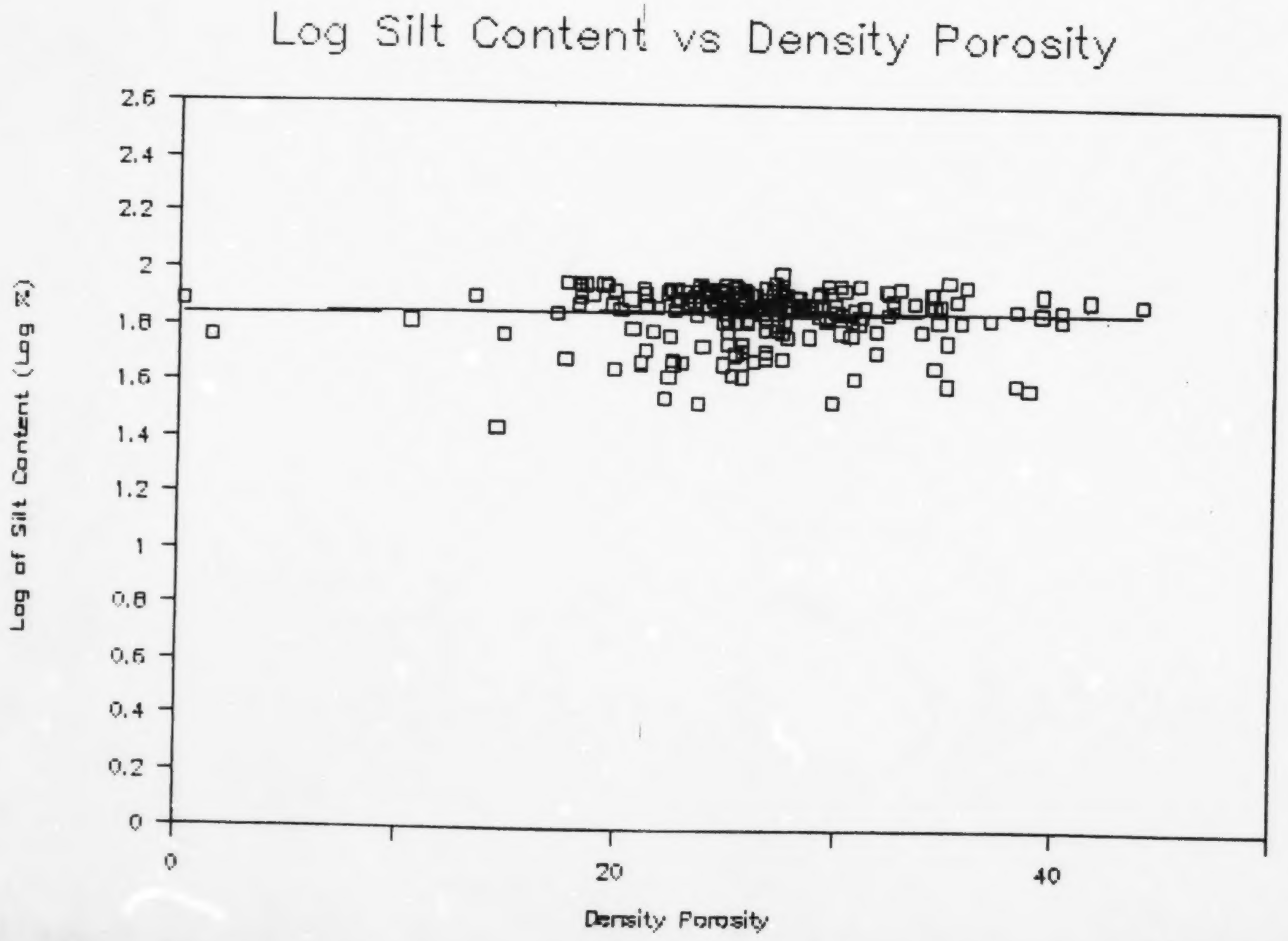
```
              Regression Output:
Constant                          72.39346
Std Err of Y Est                  14.05090
R Squared                          0.00003          R Value  0.005018
No. of Observations               219.000
Degrees of Freedom                217.000

X Coefficient(s)   0.01218
Std Err of Coef.   0.16470                         Y=0.012*X+72.393
```

Regression Analysis Output for
Log of Silt Content (Log %) vs Density Porosity

```
              Regression Output:
Constant                          1.84356
Std Err of Y Est                  0.09801
R Squared                         0.00034          R Value  0.018541
No. of Observations               219.000
Degrees of Freedom                217.000

X Coefficient(s)   0.00031
Std Err of Coef.   0.00115                         Y=0.0003*X+1.844
```

Silt Content (%) vs Density Porosity

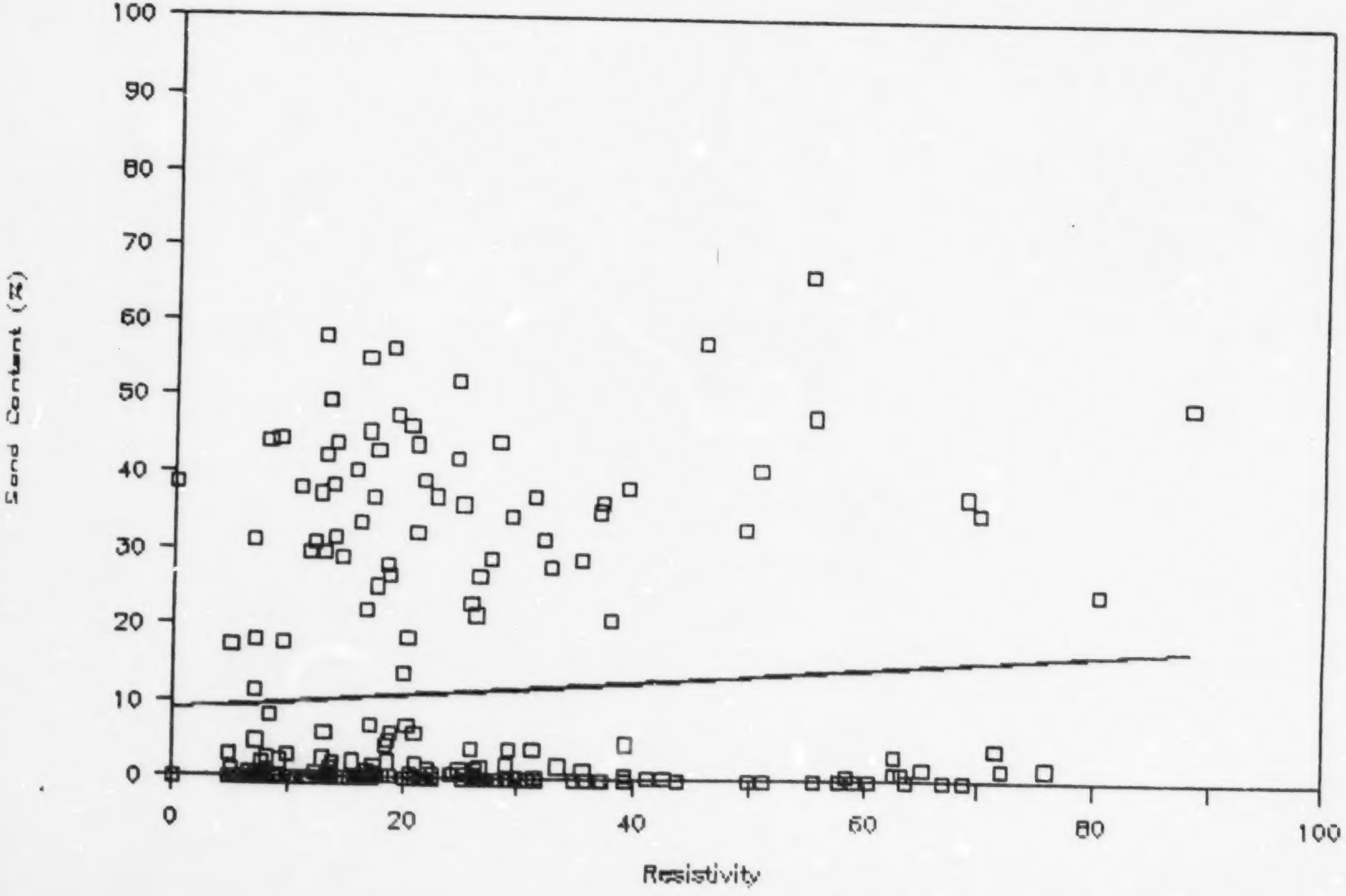



Log Silt Content vs Density Porosity
2.6
2.4
2.2
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
Log of Silt Content (Log %)
0
20
40
Density Porosity

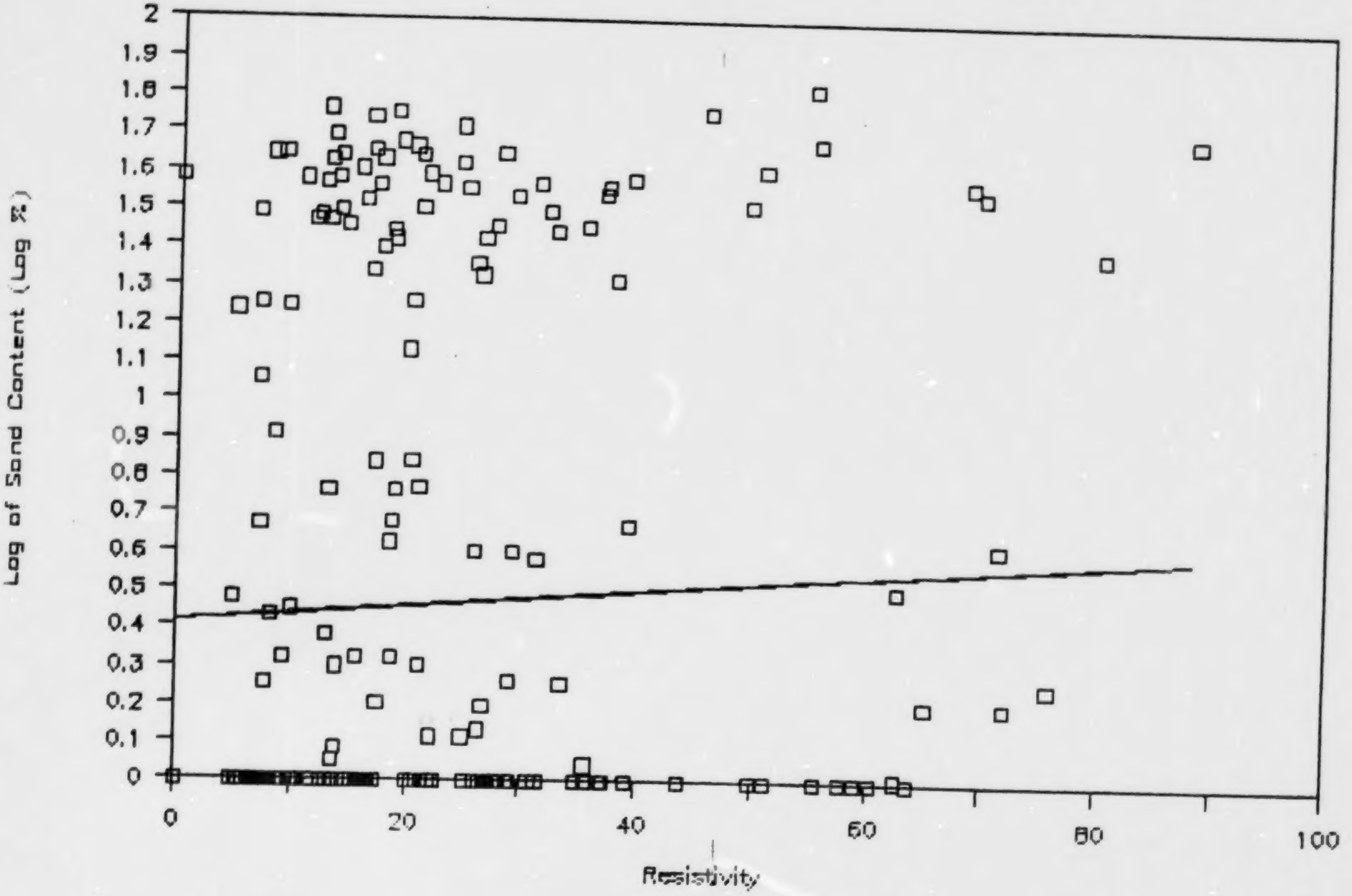
```
Regression Analysis Output for
       Sand Content (%) vs Resistivity Log


       Regression Output:
Constant                          8.896
Std Err of Y Est                 17.116
R Squared                         0.010        R Value     0.100
No. of Observations             219.000
Degrees of Freedom              217.000

X Coefficient(s)      0.098
Std Err of Coef.      0.066                    Y=0.098*X+8.896
```

```
Regression Analysis Output for
       Log of Sand Content (Log %) vs Resistivity Log


       Regression Output:
Constant                          0.415
Std Err of Y Est                  0.754
R Squared                         0.002        R Value     0.049
No. of Observations             219.000
Degrees of Freedom              217.000

X Coefficient(s)      0.002
Std Err of Coef.      0.003                    Y=0.002*X+0.415
```

Sand Content (%) vs Resistivity Log



Log Sand Content (%) vs Resistivity Log

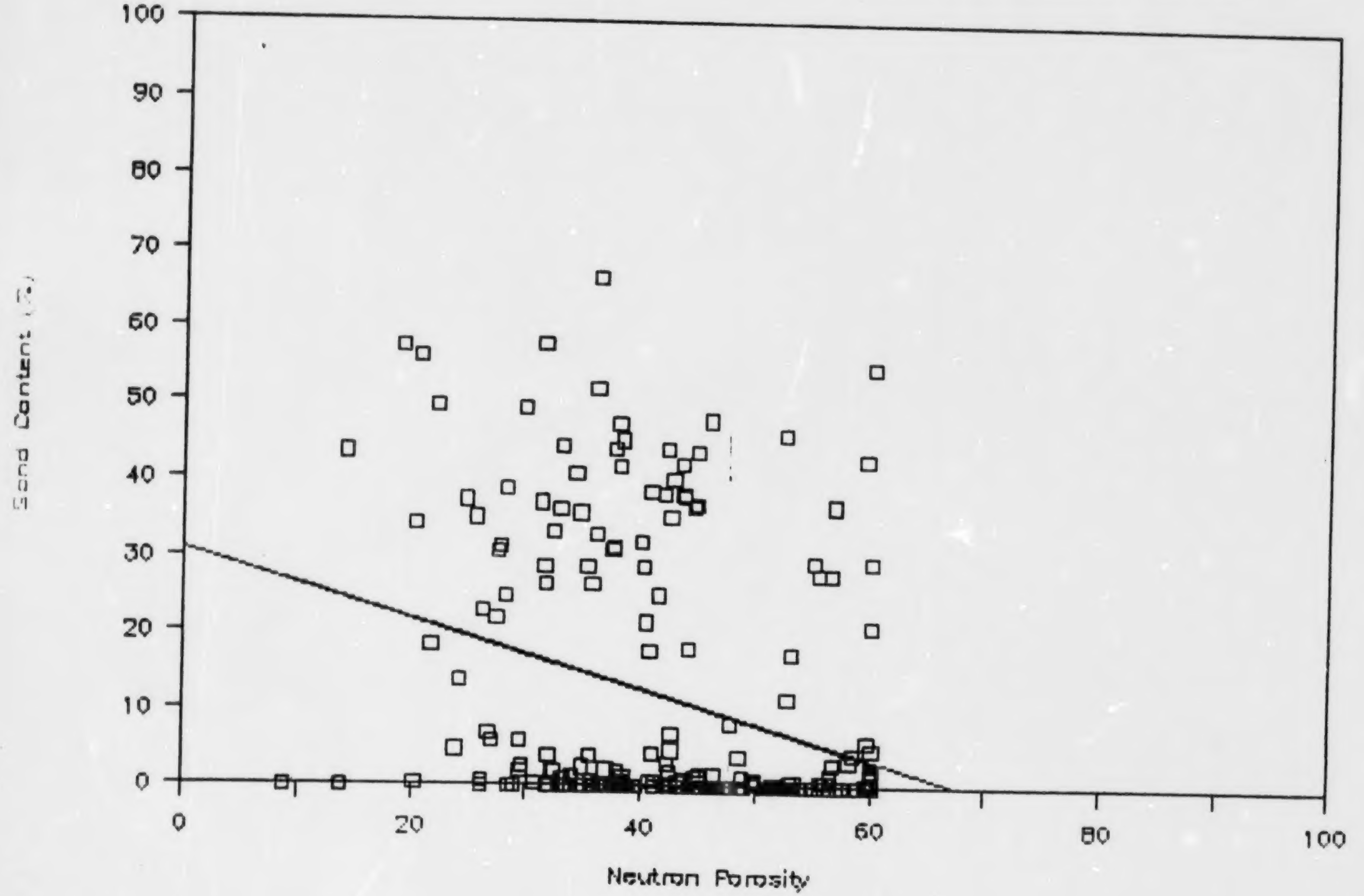


Regression Analysis Output for
Sand Content (%) vs Neutron Porosity Log

```
          Regression Output:
Constant                        30.831
Std Err of Y Est                16.405
R Squared                        0.090         R Value      0.301
No. of Observations            219.000
Degrees of Freedom             217.000

X Coefficient(s)      -0.456
Std Err of Coef.       0.098                   Y=-0.456*X+30.831
```

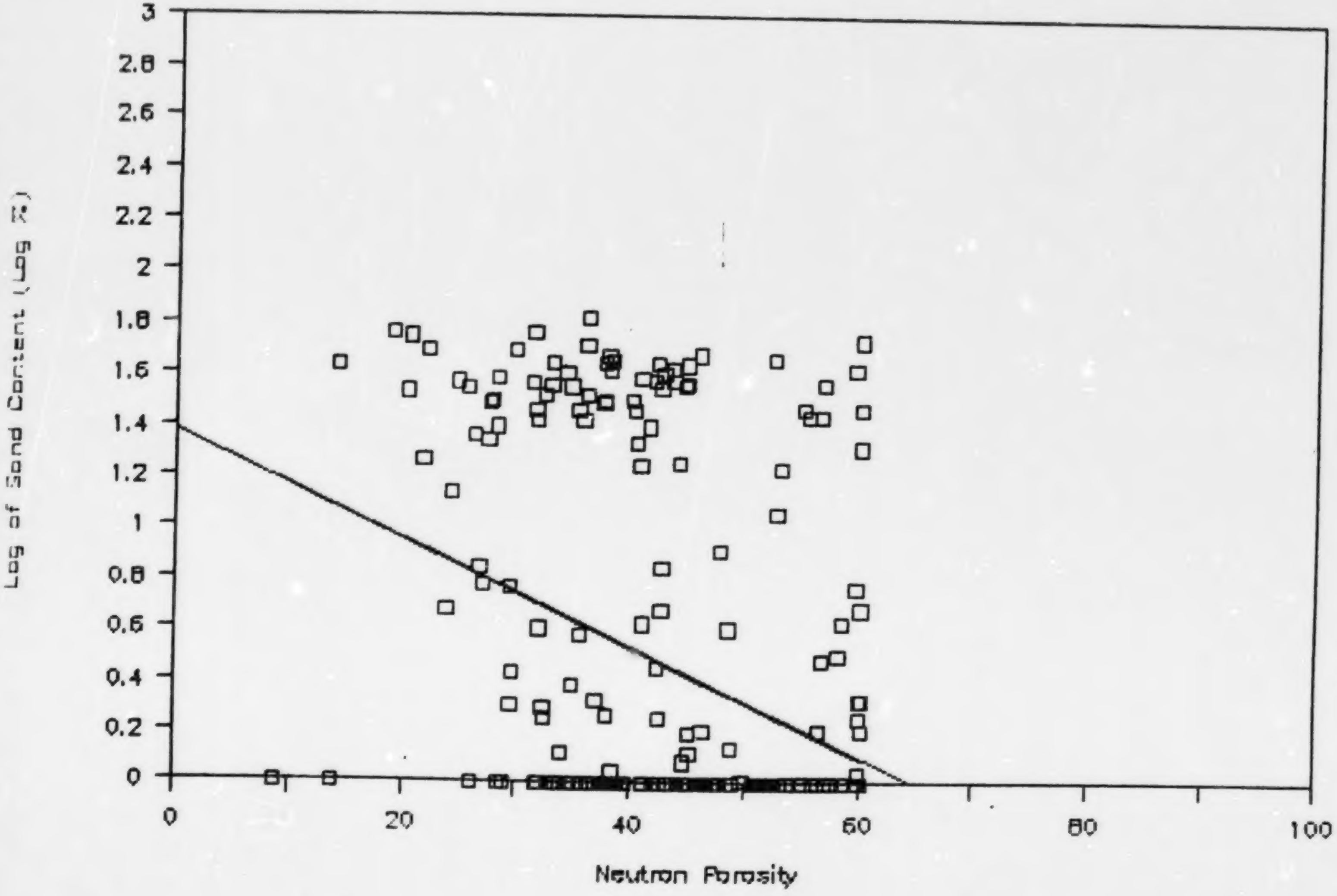
Regression Analysis Output for
Log of Sand Content (Log %) vs Neutron Porosity Log

```
          Regression Output:
Constant                         1.381
Std Err of Y Est                 0.715
R Squared                        0.103         R Value      0.320
No. of Observations            219.000
Degrees of Freedom             217.000

X Coefficient(s)      -0.021
Std Err of Coef.       0.004                   Y=-0.021*X+1.381
```



Sand Content(%) vs Neutron Porosity Log

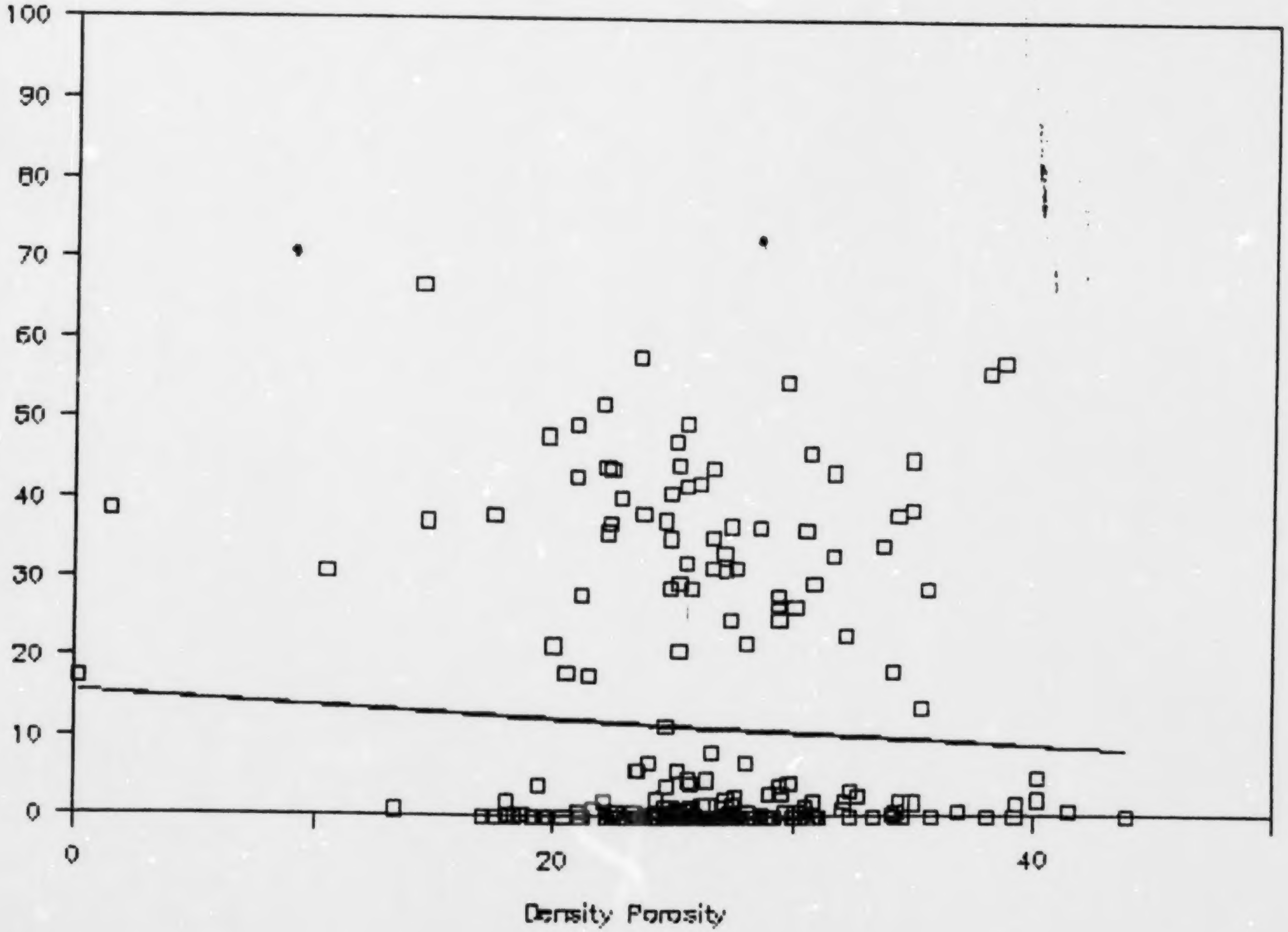
Sand Content vs Neutron Porosity Log

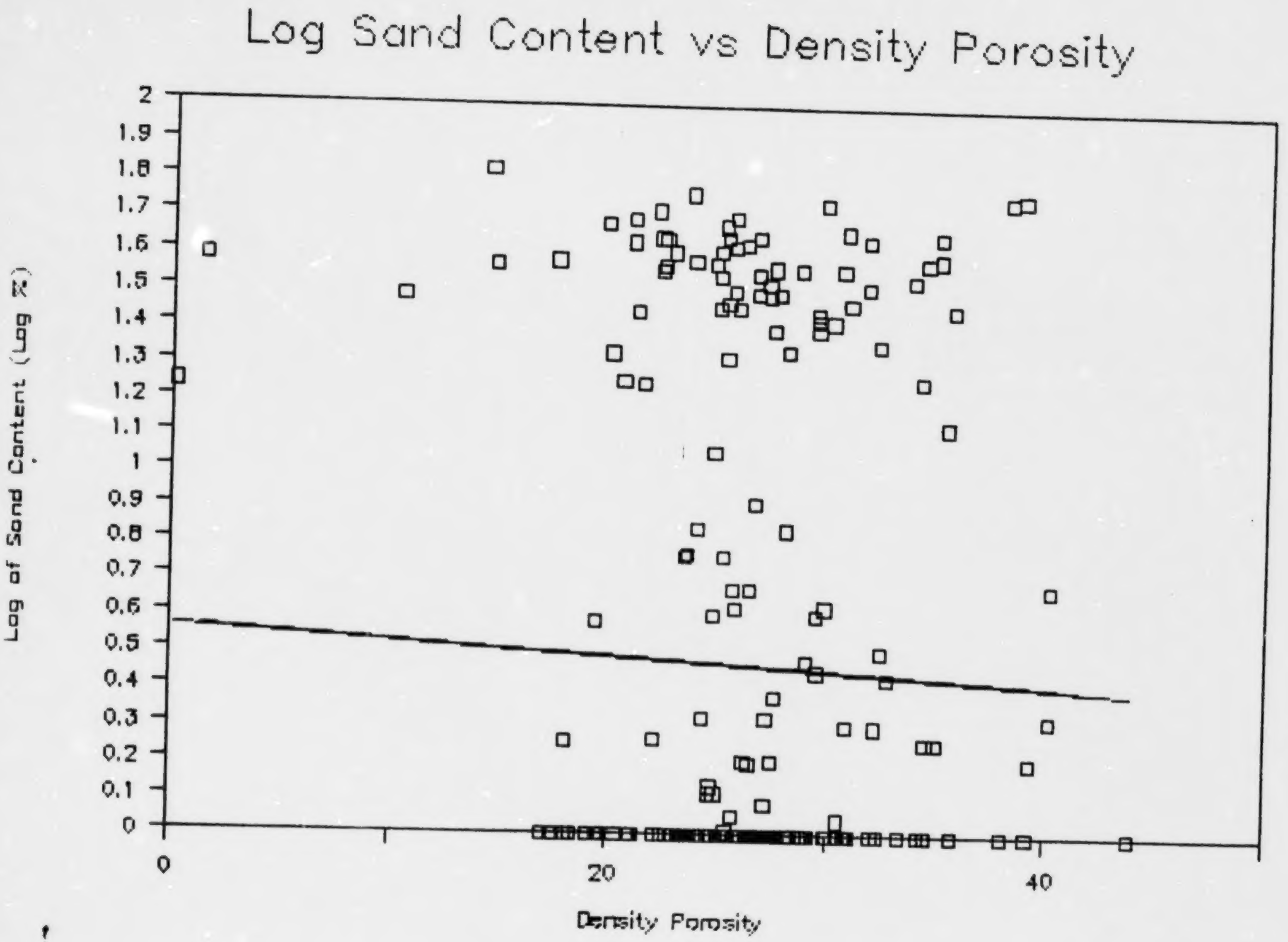


```
Regression Analysis Output for
        Sand Content (%) vs Density Porosity

            Regression Output:
Constant                            15.447
Std Err of Y Est                    17.176
R Squared                            0.003          R Value  0.054357
No. of Observations                219.000
Degrees of Freedom                 217.000

X Coefficient(s)     -0.161
Std Err of Coef.      0.201                         Y=-0.161*X+15.447
```

```
Regression Analysis Output for
        Log of Sand Content (Log %) vs Density Porosity

            Regression Output:
Constant                             0.562
Std Err of Y Est                     0.754
R Squared                            0.001          R Value  0.028595
No. of Observations                219.000
Degrees of Freedom                 217.000

X Coefficient(s)     -0.004
Std Err of Coef.      0.009                         Y=-0.004*X+0.562
```

Sand Content (%) vs Density Porosity

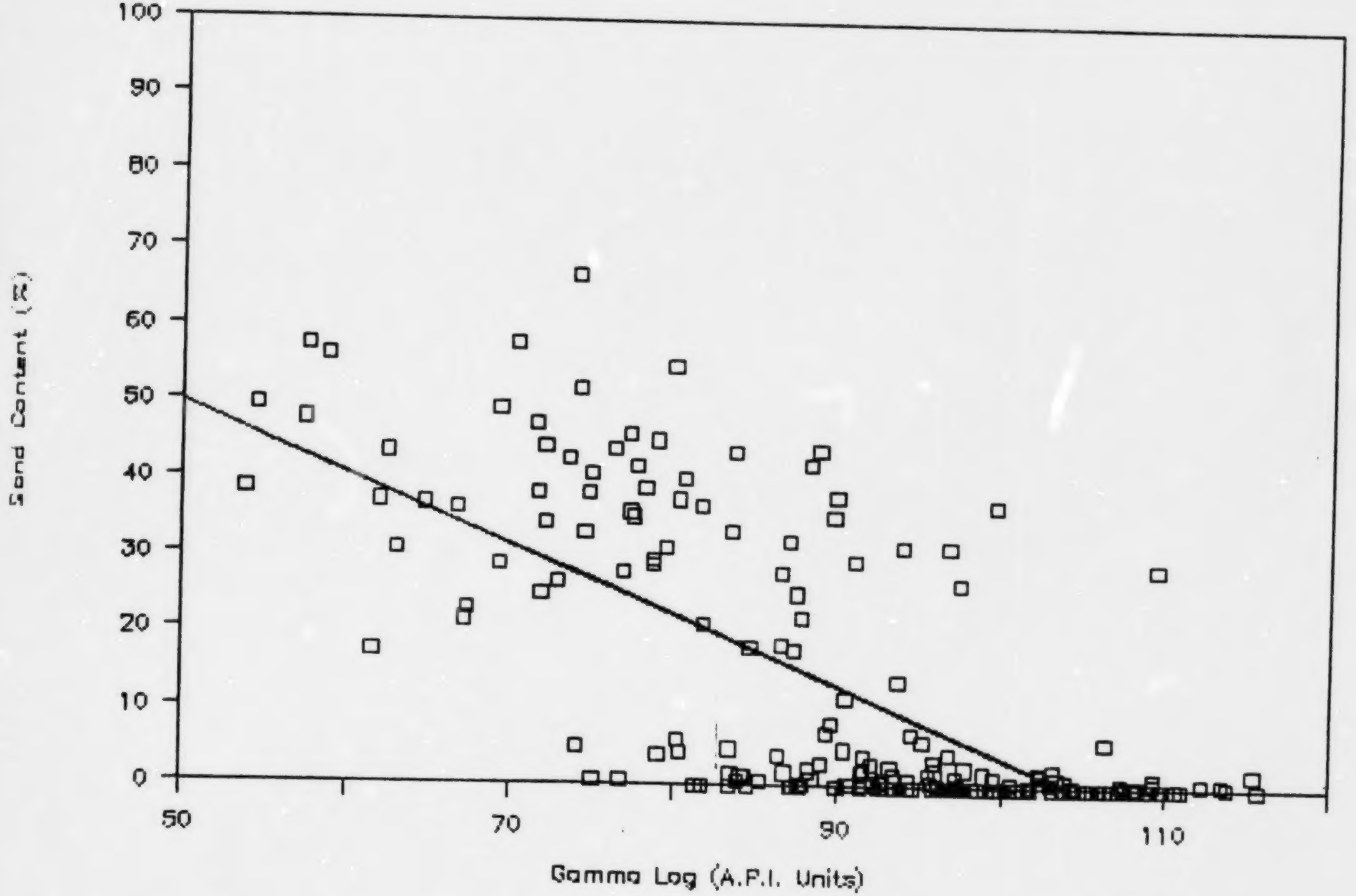


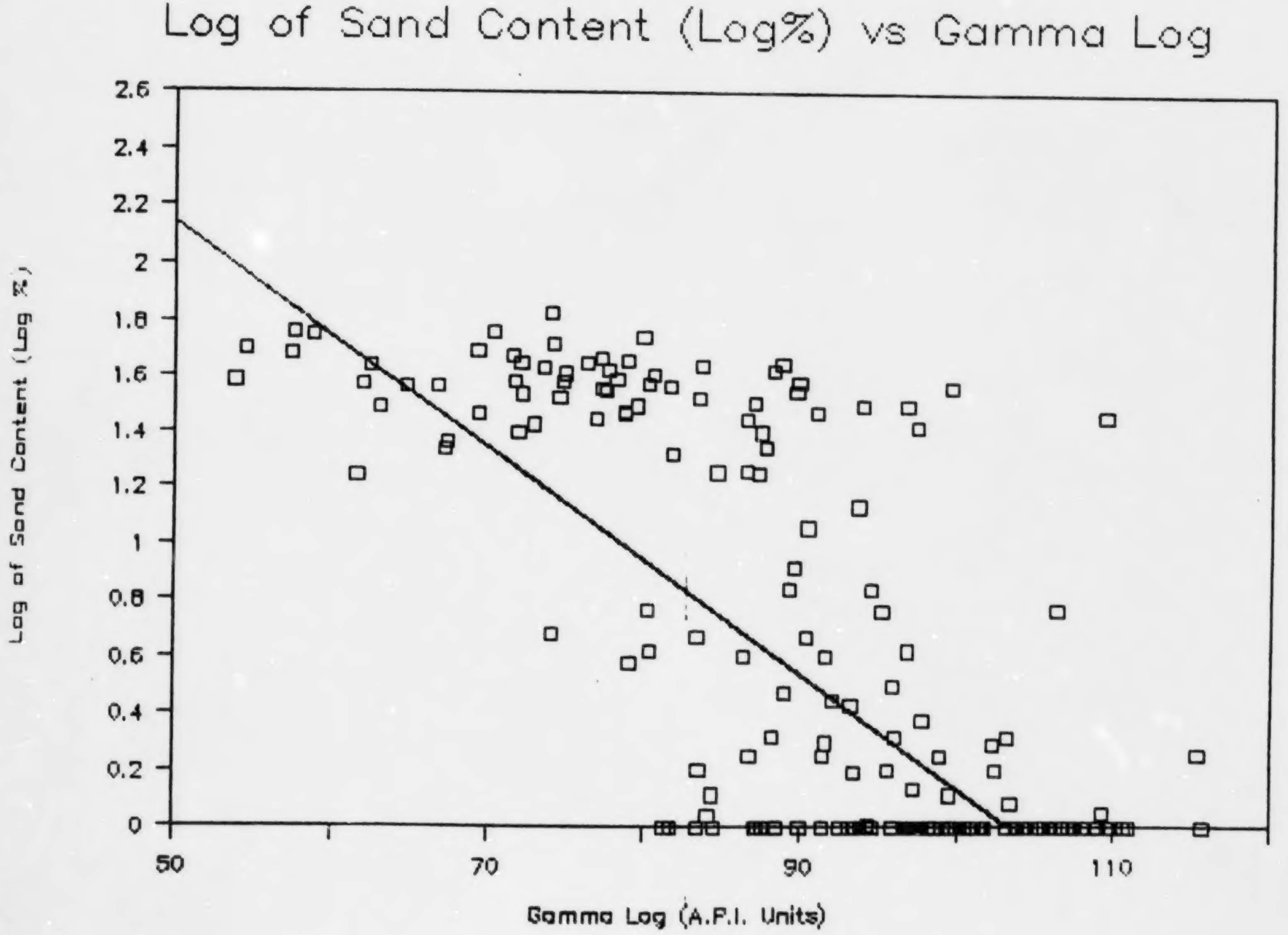

Log Sand Content vs Density Porosity
Log of Sand Content (Log %)
2
1.9
1.8
1.7
1.6
1.5
1.4
1.3
1.2
1.1
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
20
40
Density Porosity

```
Regression Analysis Output for
        Sand Content (%) vs Gamma Log


        Regression Output:
Constant                        95.681
Std Err of Y Est                11.925
R Squared                        0.519         R Value  0.720715
No. of Observations            219.000
Degrees of Freedom             217.000

X Coefficient(s)    -0.920
Std Err of Coef.     0.060                     Y=-0.920*X+95.681
```

```
Regression Analysis Output for
        Log of Sand Content (Log %) vs Gamma Log


        Regression Output:
Constant                         4.150
Std Err of Y Est                 0.526
R Squared                        0.514         R Value     0.717
No. of Observations            219.000
Degrees of Freedom             217.000

X Coefficient(s)    -0.040
Std Err of Coef.     0.003                     Y=-0.040*X+4.150
```

Sand Content (%) vs Gamma Log

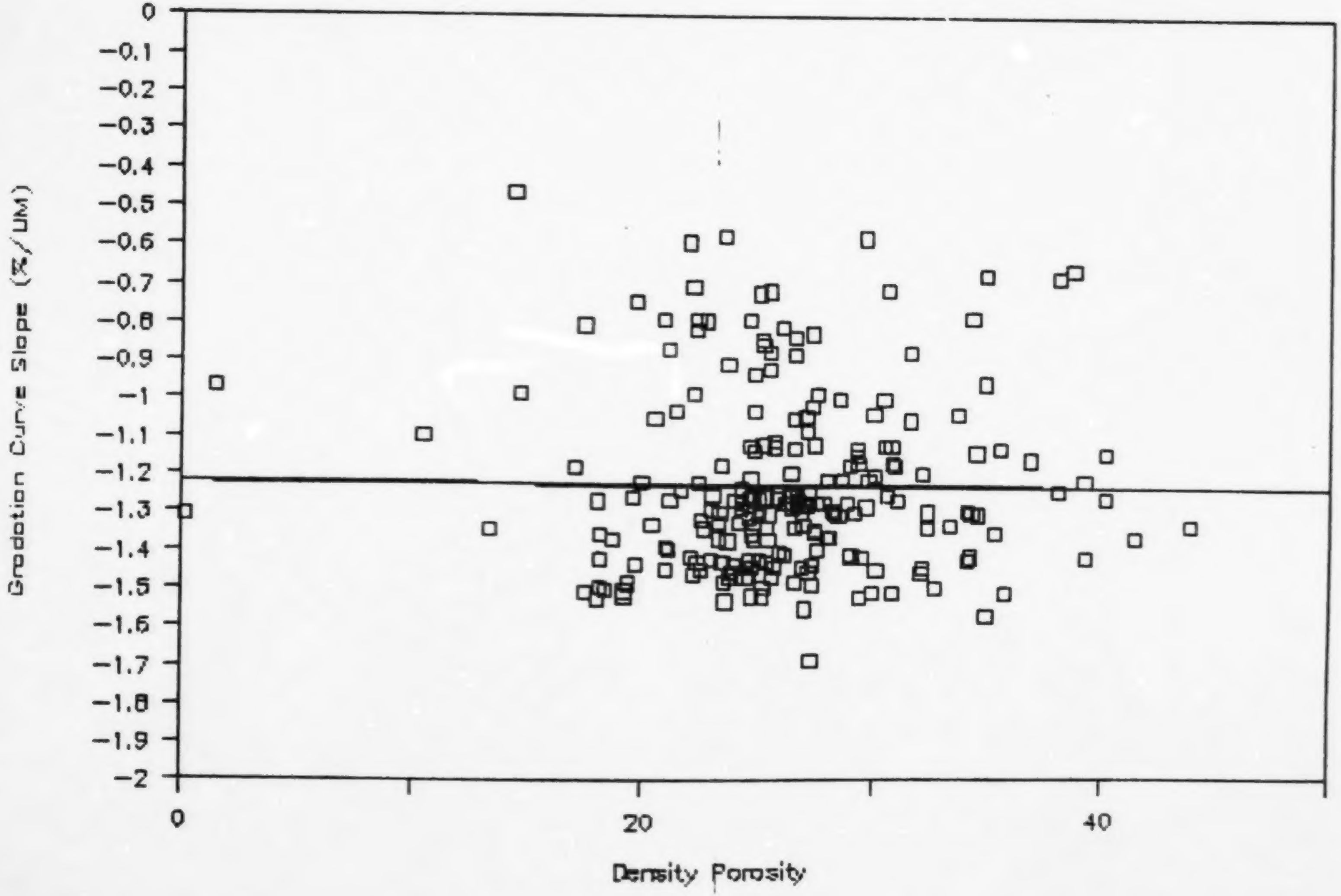



Log of Sand Content (Log%) vs Gamma Log
Log of Sand Content (Log %)
2.6
2.4
2.2
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
50
70
90
110
Gamma Log (A.P.I. Units)

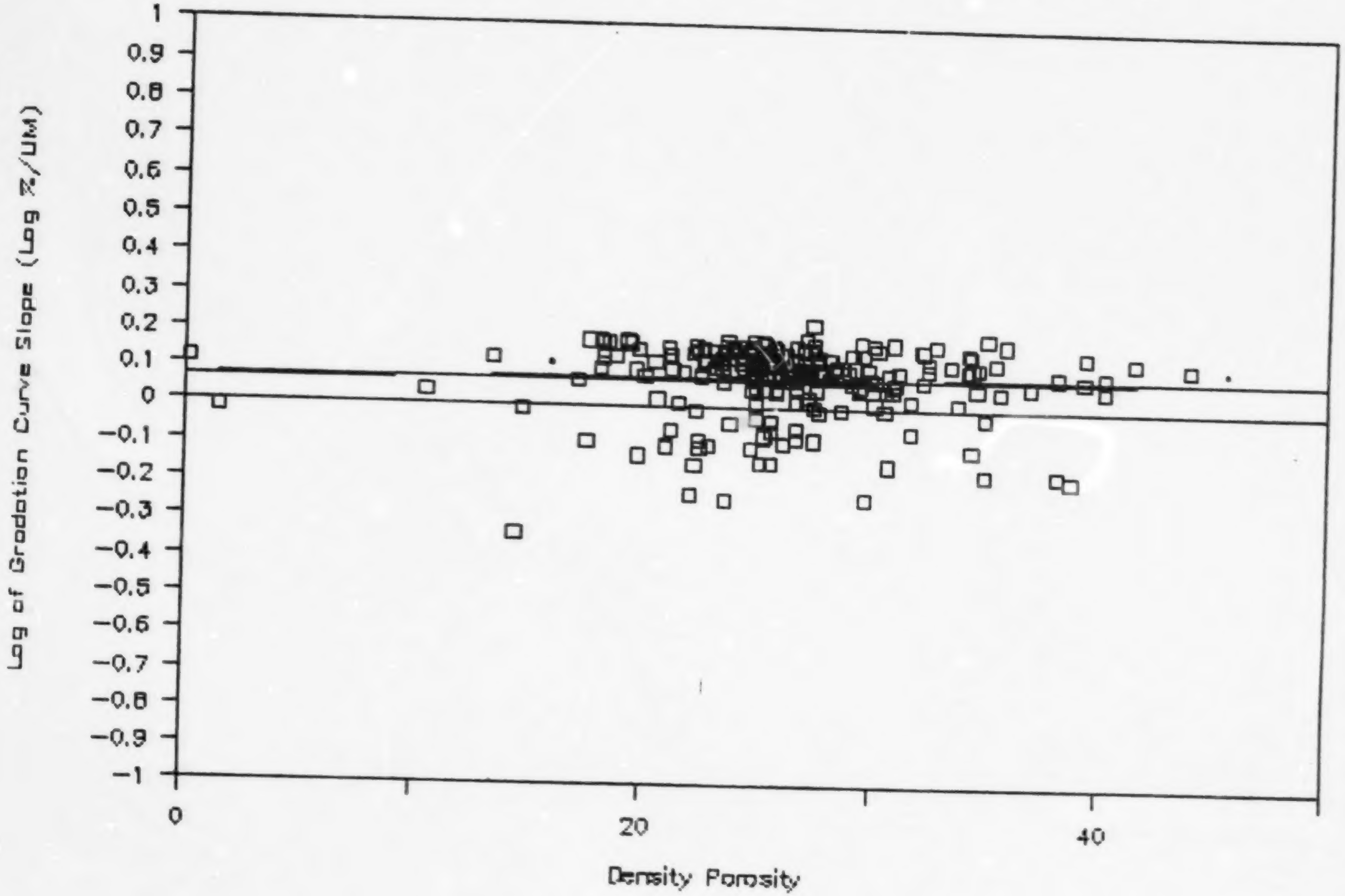
```
Regression Analysis Output for
        Gradation Curve Slope vs Density Porosity


        Regression Output:
Constant                         -1.223
Std Err of Y Est                  0.237
R Squared                         0.000        R Value        0.005
No. of Observations             219.000
Degrees of Freedom              217.000

X Coefficient(s)  -0.00021
Std Err of Coef.   0.00278                     Y=-0.0002*X-1.223
```

```
Regression Analysis Output for
        Log of Gradation Curve Slope vs Density Porosity Log


        Regression Output:
Constant                        0.07124
Std Err of Y Est                0.09801
R Squared                       0.00034  --   R Value   0.018541225
No. of Observations             219.000
Degrees of Freedom              217.000

X Coefficient(s)  0.00031
Std Err of Coef.  0.00115                     Y=0.0003*X+0.071
```

Curve Slope (%/UM) vs Density Porosity

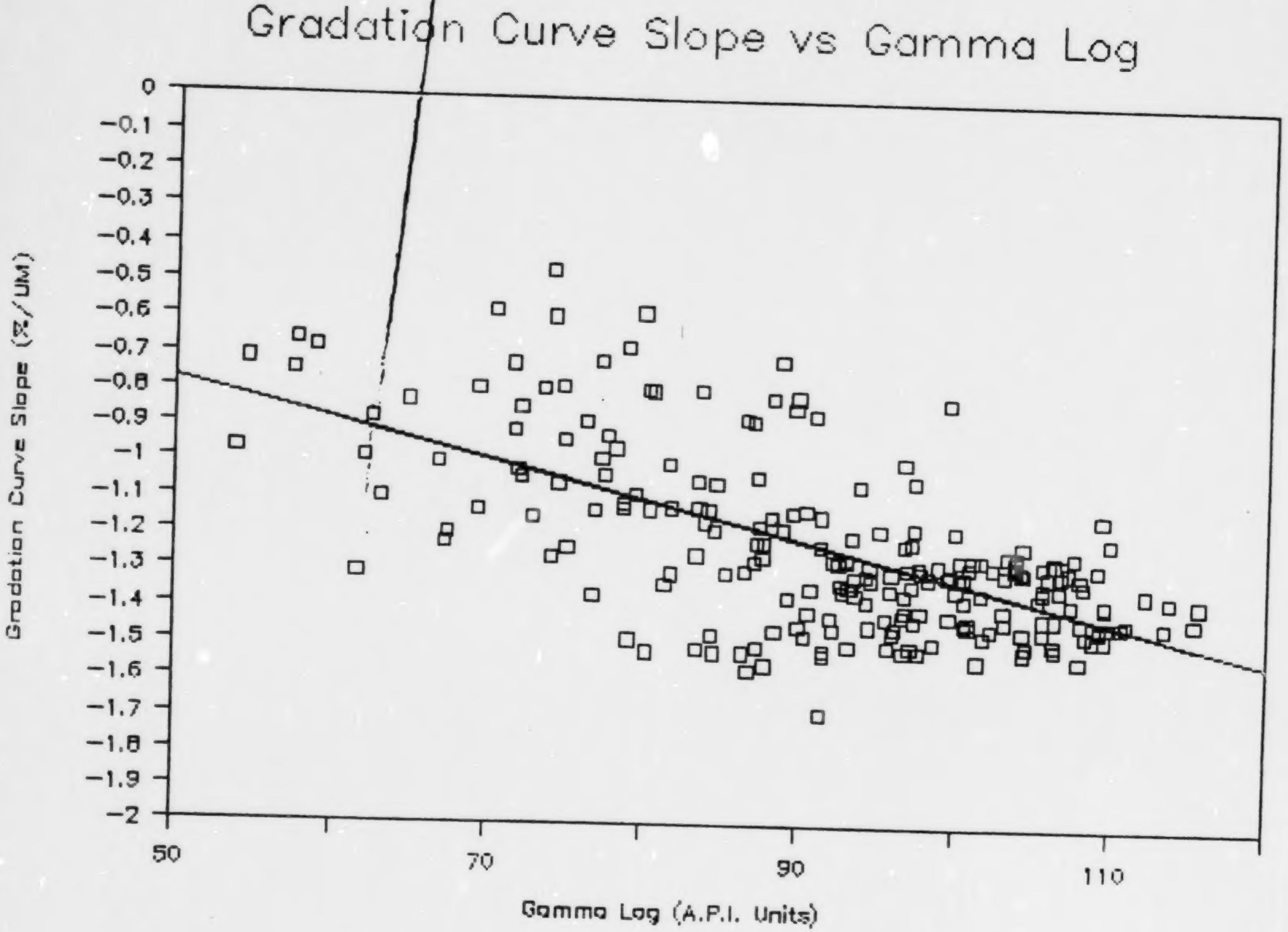


Log Curve Slope Vs Density Porosity

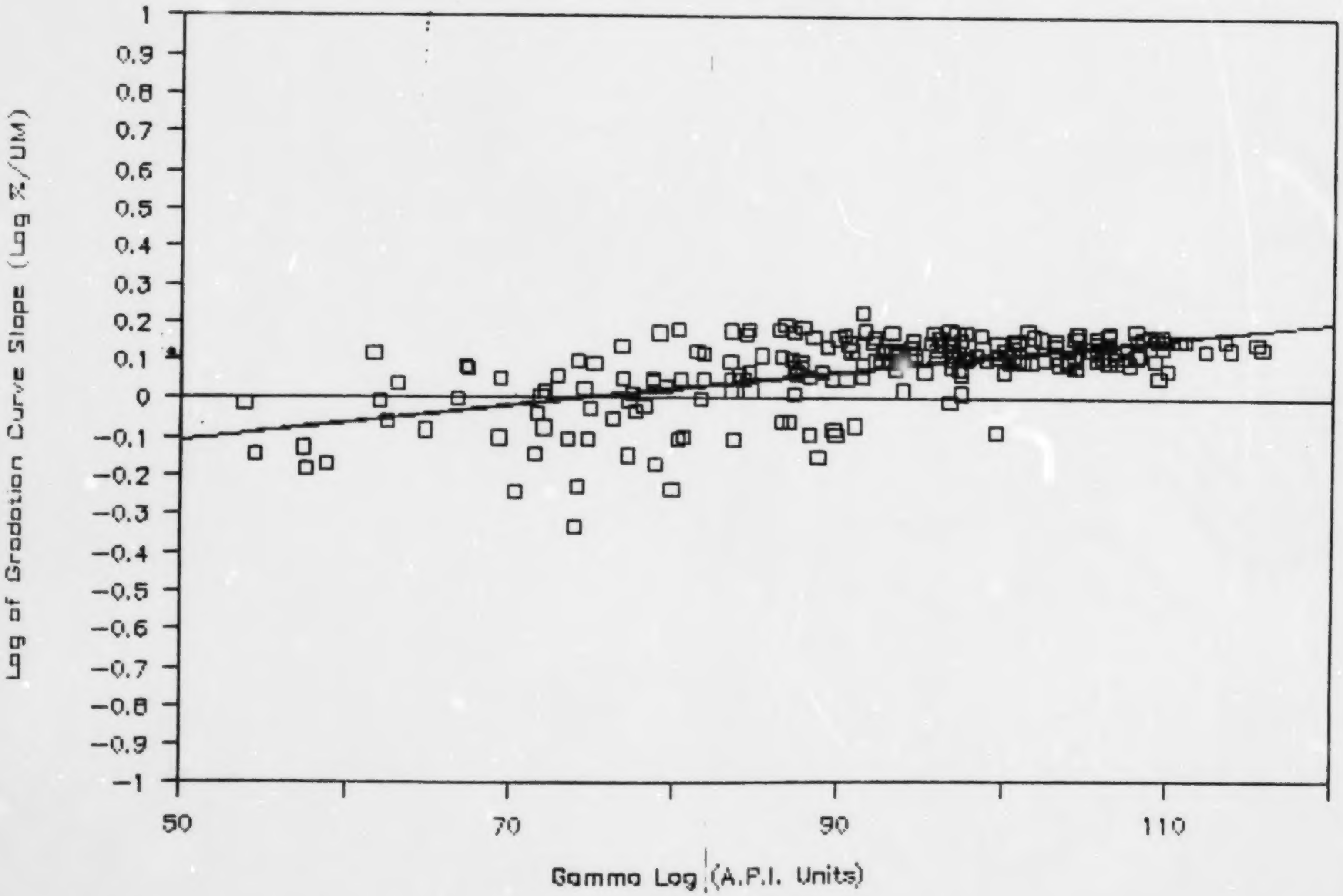


```
Regression Analysis Output for
        Gradation Curve Slope vs Gamma Log


        Regression Output:
Constant                       -0.230
Std Err of Y Est                0.187
R Squared                       0.381        R Value         0.617
No. of Observations           219.000
Degrees of Freedom            217.000

X Coefficient(s)  -0.01087
Std Err of Coef.   0.00094                   Y=-0.011*X-0.230
```

```
Regression Analysis Output for
        Log of Gradation Curve Slope vs Gamma Log


        Regression Output:
Constant                       -0.330
Std Err of Y Est                0.077
R Squared                       0.377        R Value   0.613794865
No. of Observations           219.000
Degrees of Freedom            217.000

X Coefficient(s)   0.00446
Std Err of Coef.   0.00039                   Y=0.004*X-0.330
```


Gradation Curve Slope vs Gamma Log
Gradation Curve Slope (%/UM)
0
−0.1
−0.2
−0.3
−0.4
−0.5
−0.6
−0.7
−0.8
−0.9
−1
−1.1
−1.2
−1.3
−1.4
−1.5
−1.6
−1.7
−1.8
−1.9
−2
50
70
90
110
Gamma Log (A.P.I. Units)

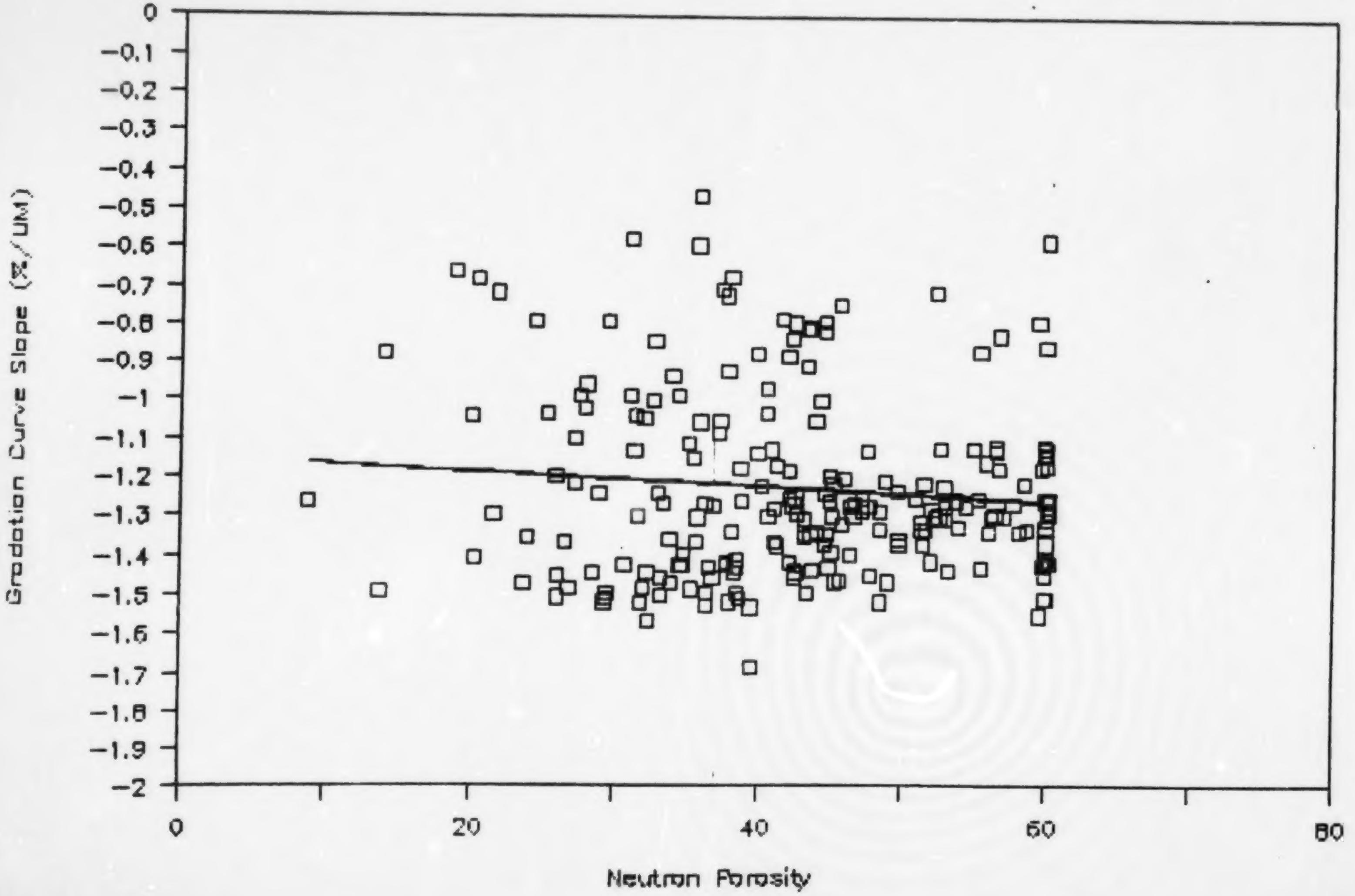
Log Gradation Curve Slope vs Gamma Log



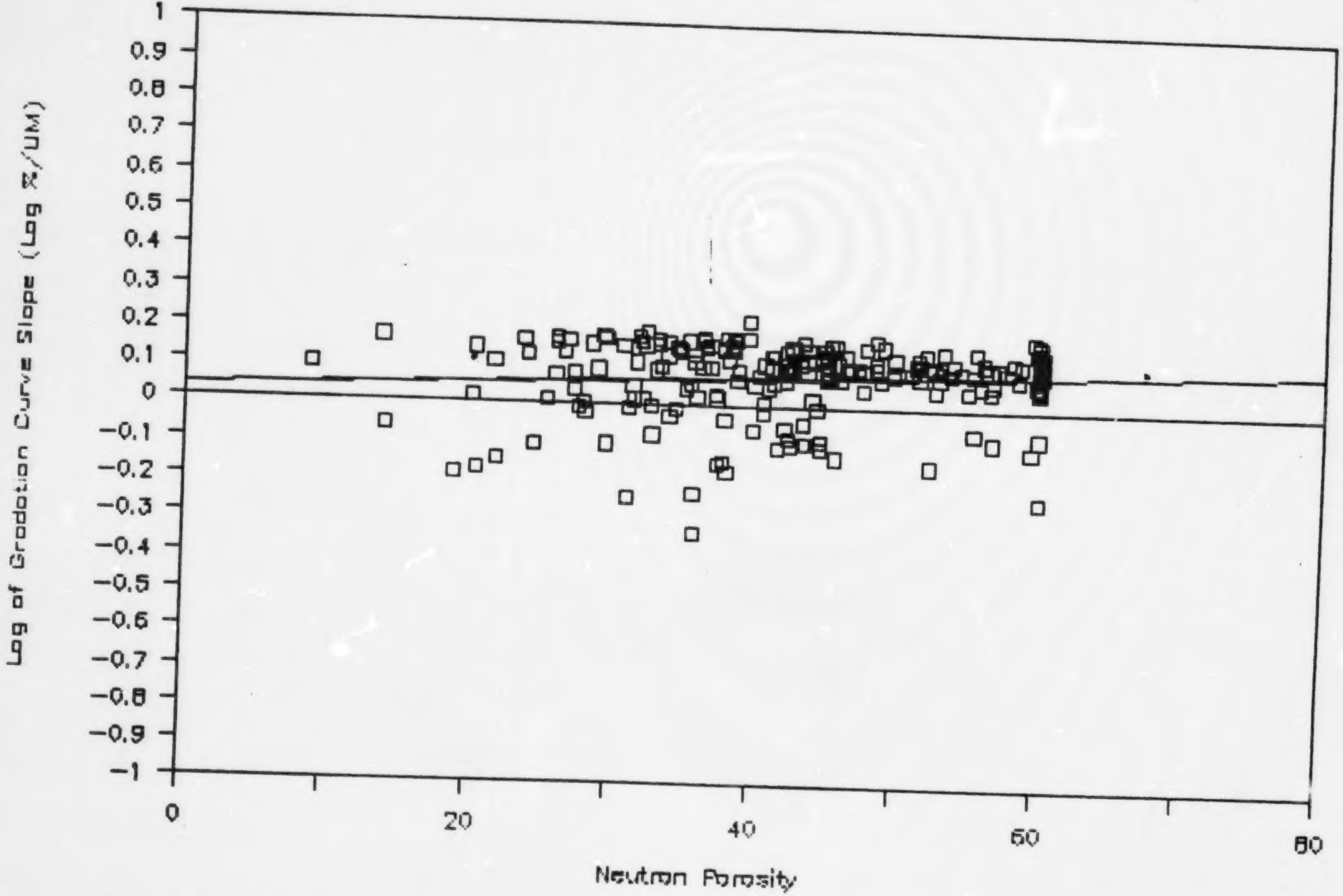
```
Regression Analysis Output for
        Gradation Curve Slope vs Neutron Porosity Log

        Regression Output:
Constant                           -1.143
Std Err of Y Est                    0.236
R Squared                           0.009       R Value        0.094
No. of Observations               219.000
Degrees of Freedom                217.000

X Coefficient(s)  -0.00197
Std Err of Coef.   0.00142                      Y=-0.002*X-1.143
```

```
Regression Analysis Output for
        Log of Gradation Curve Slope vs Neutron Porosity Log

        Regression Output:
Constant                            0.036
Std Err of Y Est                    0.097
R Squared                           0.014       R Value  0.116572583
No. of Observations               219.000
Degrees of Freedom                217.000

X Coefficient(s)   0.00101
Std Err of Coef.   0.00058                      Y=0.001*X+0.036
```

Curve Slope (%/UM) vs Neutron Porosity



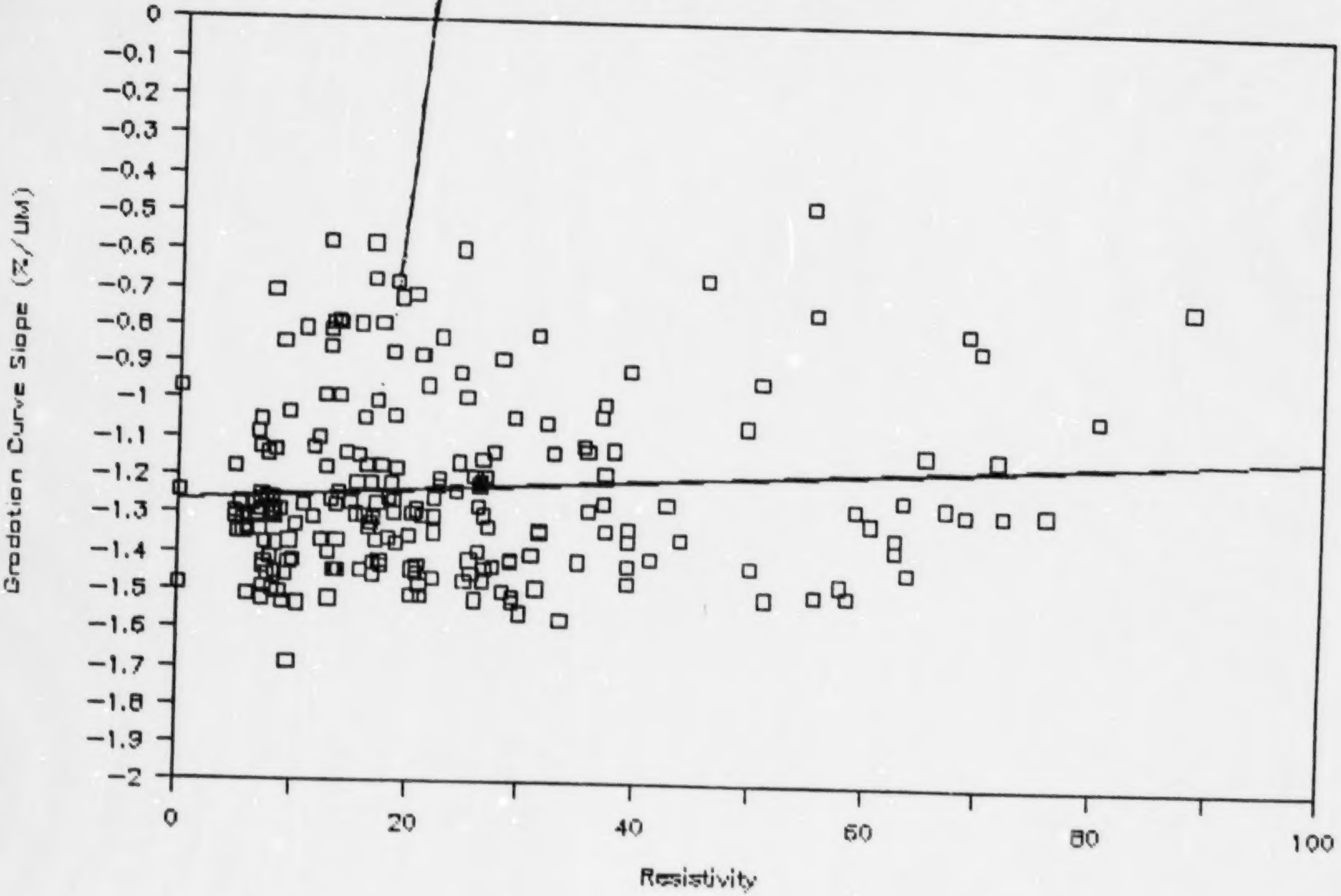
Log of Curve Slope vs Neutron Porosity

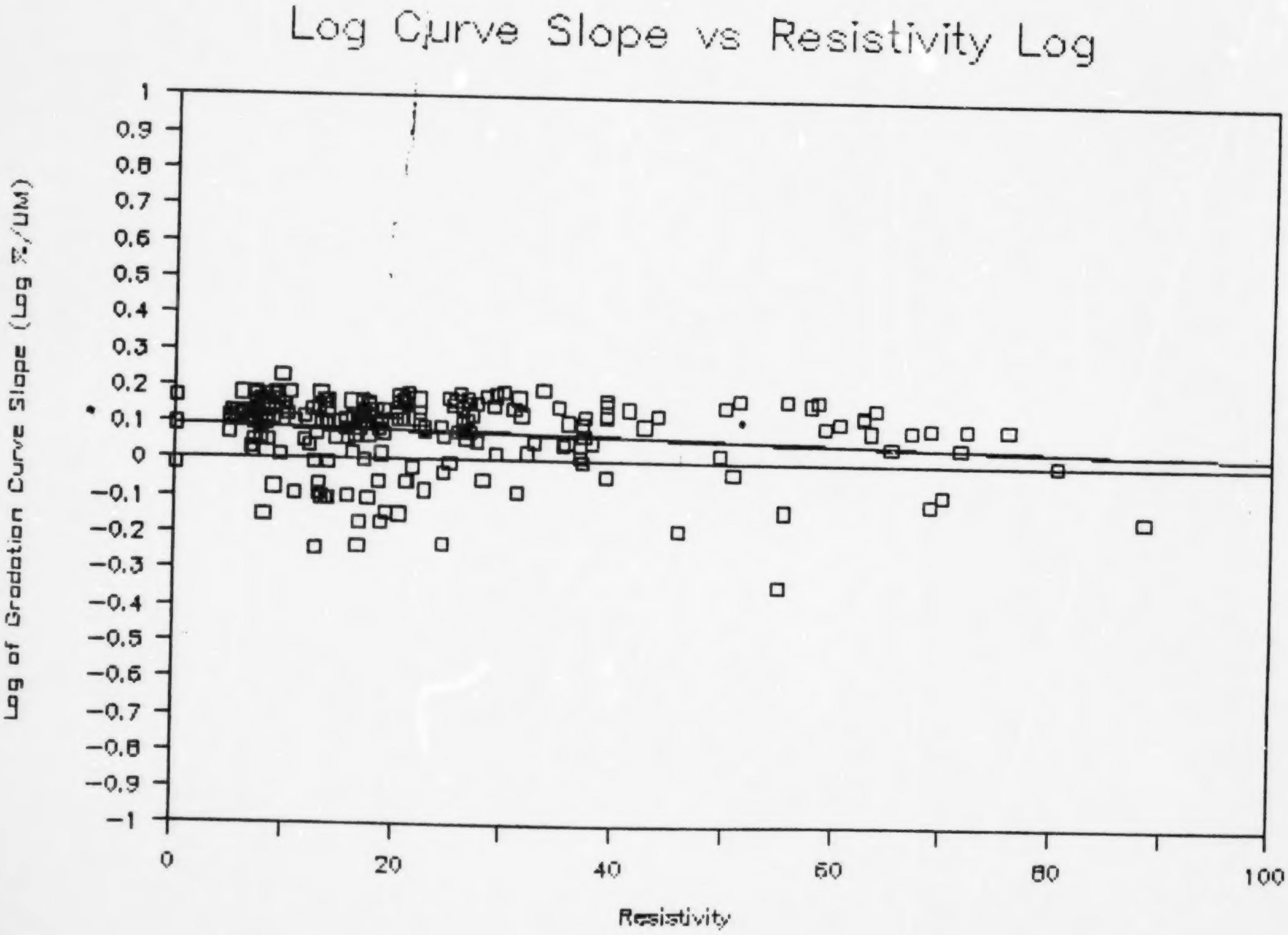


```
Regression Analysis Output for
         Gradation Curve Slope vs Resistivity Log


         Regression Output:
Constant                         -1.263
Std Err of Y Est                  0.236
R Squared                         0.012        R Value   0.109073776
No. of Observations             219.000
Degrees of Freedom              217.000

X Coefficient(s)   0.00148
Std Err of Coef.   0.00091                     Y=0.001*X-1.263
```

```
Regression Analysis Output for
         Log of Gradation Curve Slope vs Resistivity Log


         Regression Output:
Constant                          0.094
Std Err of Y Est                  0.097
R Squared                         0.013        R Value   0.113605108
No. of Observations             219.000
Degrees of Freedom              217.000

X Coefficient(s)  -0.00064
Std Err of Coef.   0.00038                     Y=-0.0006*X+0.094
```

Slope (%/UM) vs Resistivity Log





Log Curve Slope vs Resistivity Log

APPENDIX V

HYDROGEOLOGICAL COAL CORRELATIONS

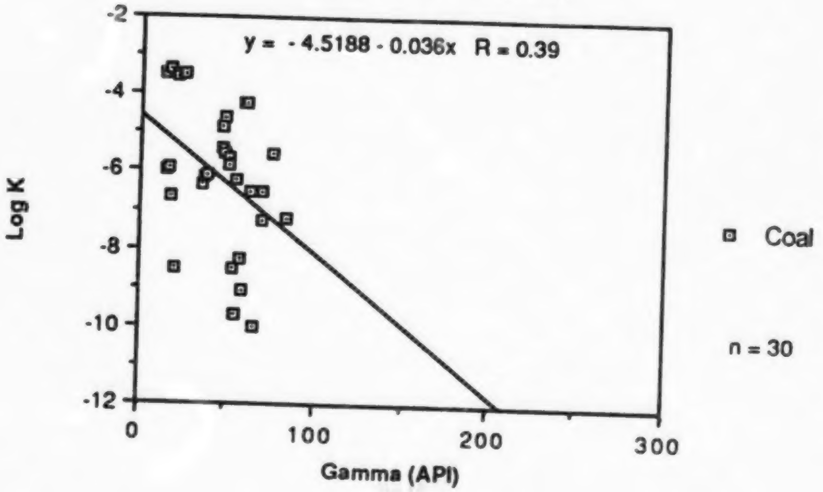
Detailed Procedure of Data Search and Analysis Followed For Hydrogeologic Correlations

The collection, organization and preparation of data to be used for correlations proved to be more of a difficult and time consuming task than originally anticipated. Several steps had to be carried out before the actual correlations could even be made. The list below shows the analytical process followed for the data workup.

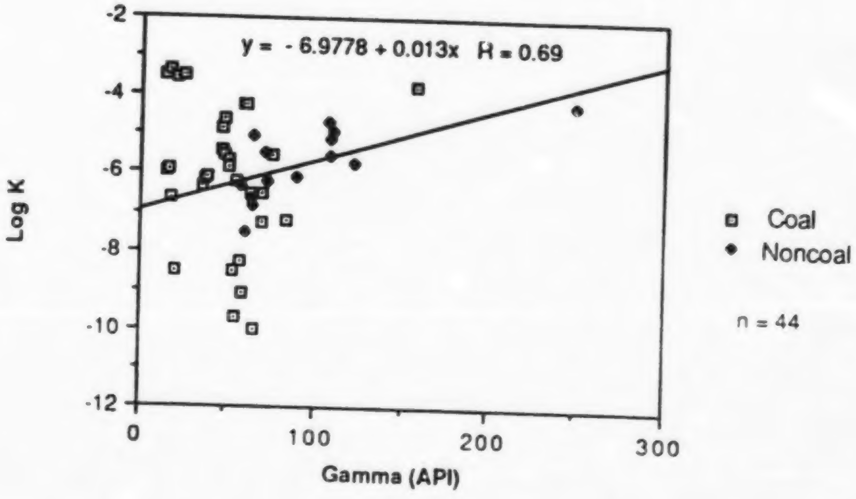
- parameters of interest identified.
- a search of existing hydrogeologic data from ARC projects checked for potential use (PHRP and Highwall Stability Studies).
- data set narrowed down to records with geophysical log data.
- geophysical log data retrieval was first attempted from magnetic tape.
- this proved unsuccessful because digital log data were in BPB field format on cassette tapes which could not be easily read into ARC computers.
- preliminary attempts at reformatting data proved too costly and time consuming (≈$50 per hole).
- for analysis, decided to proceed with a smaller data set by digitizing the hard paper copy logs for only a few holes.
- decided the target for first correlations attempt should concentrate on a single, easily identifiable lithology - coal.
- used ARC's log analysis system, Logmate on HP desktop computer to digitize paper logs.
- digitized a total of 70 logs from 14 holes at an average depth of 50m.
- 10cm increment used for producing digital value.
- digital log data were tabulated and formatted for transfer to the VAX computer.
- log data were then transfered from VAX to a Macintosh microcomputer where first analysis were carried out.
- in the Macintosh, log data was reformatted and edited to select the desired depth interval (chose log values from the exact depth interval that corresponded to depth of piezometer screen).
- log data was then dumped into spread sheet program (Microsoft Excel) for organization and manipulation.
- in Excel; log values averaged over same depth as screen intervals, hydraulic conductivity (K) values entered, calculations made to some

values to give preferred new value (velocity from sonic, density in gm/cc from density log in sdu, linearize the values of FE log and K by taking the log of those values)(Table 1).

- after edits of data finalized, data dumped into graphics presentation software program (Cricket Graph) for plotting on x/y scatter graphs.
- crossplots were made for K and the different geophysical log types.
- selected data was transfered back into VAX for analysis on SAS program to correlate K with combined sets of geophysical log values.

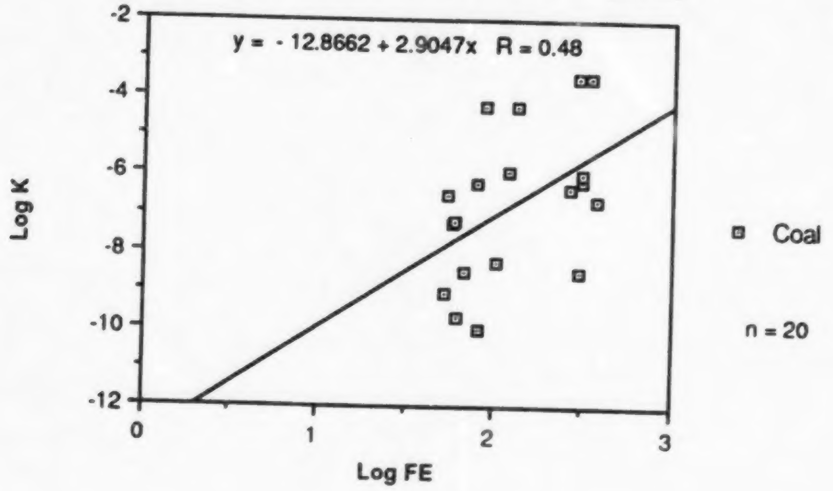


Log K vs Gamma (coal)

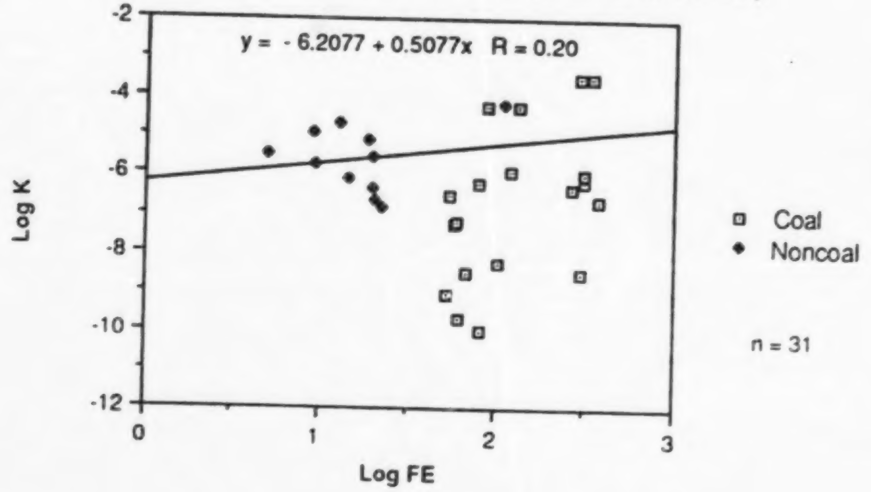


Log K vs Gamma (coal & noncoal)

Log K vs Log Focussed Electric (coal)

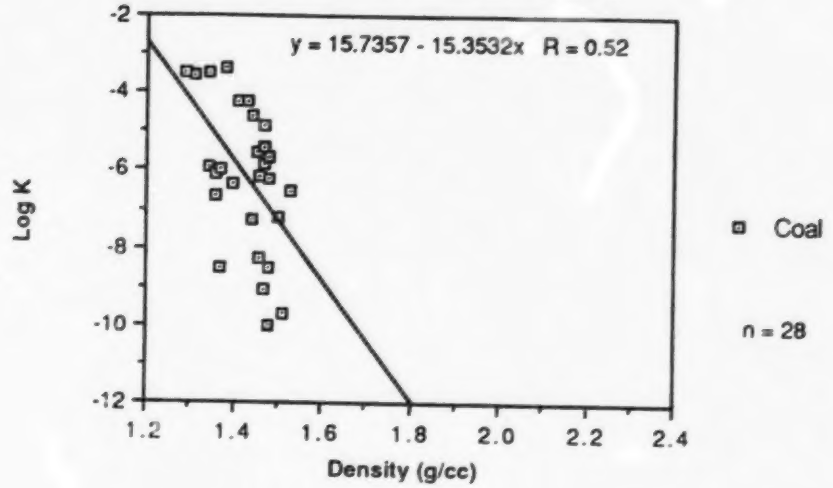


Log K vs Log Focussed Electric (coal & noncoal)

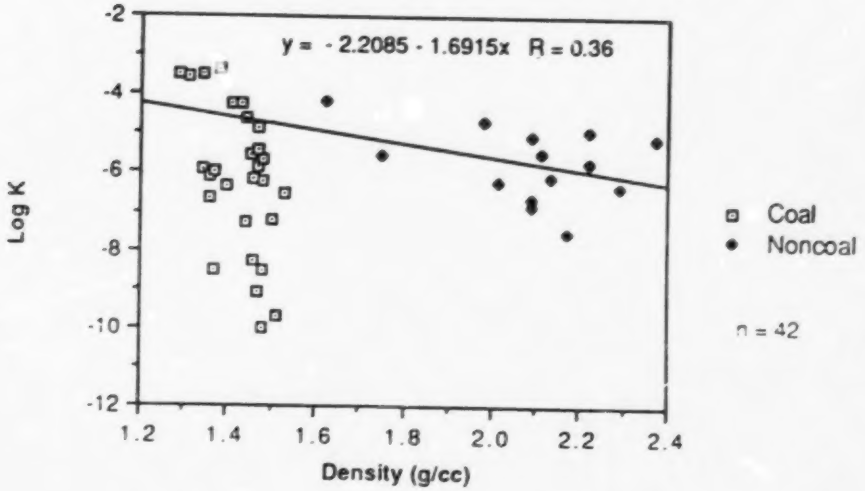


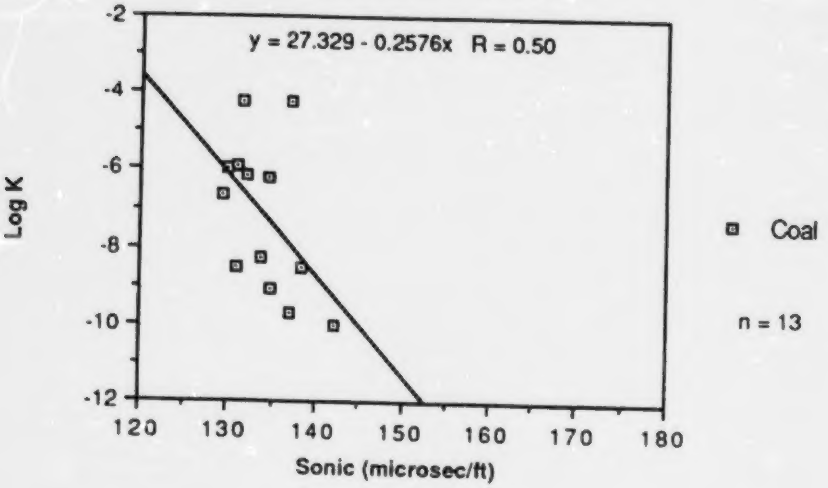
X

Log K vs Bulk Density (coal)

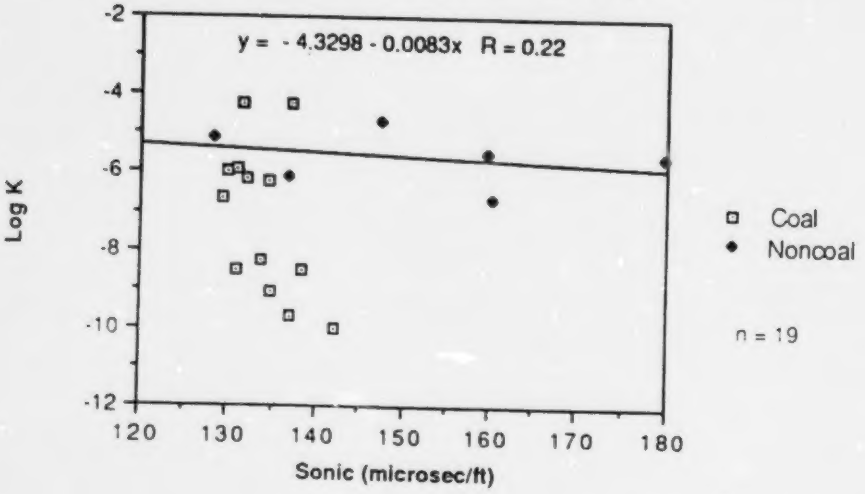


Log K vs Bulk Density (coal & noncoal)

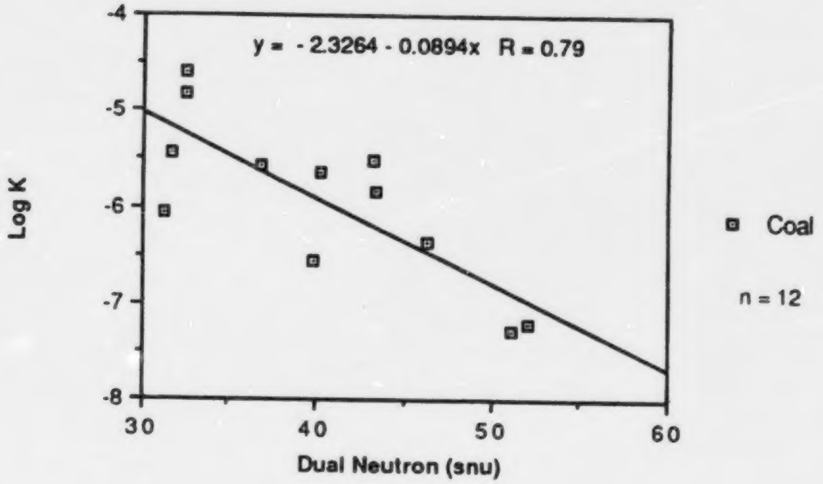


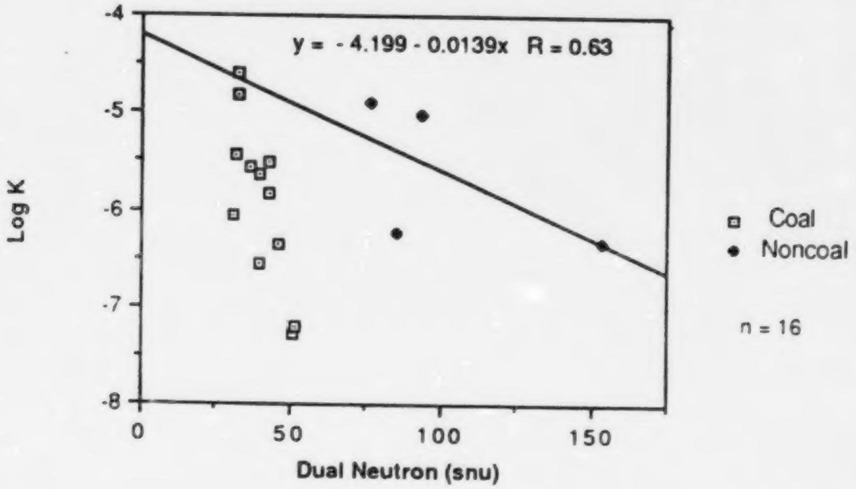


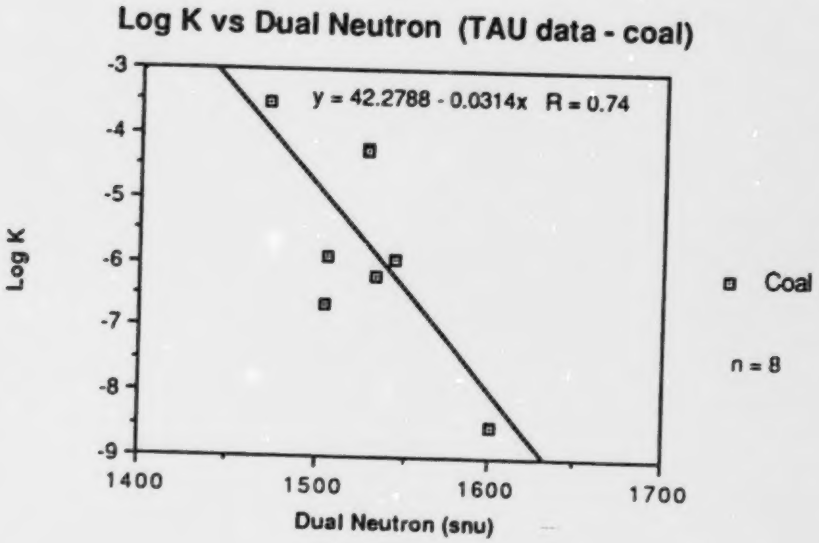
Log K vs Sonic (coal)



Log K vs Sonic (coal & noncoal)


Log K vs Dual Neutron (ARC data - coal)


Log K vs Dual Neutron (ARC data - coal & noncoal)


Log K vs Dual Neutron (TAU data - coal)